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MERADCOM/OSU ASSESSMENT AND RATING OF THE CONTAMINANT SENSITIVITY OF RELIEF VALVES .

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Fort Belvoir, Virginia 22060

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Prepared by

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13. ABSTRACT

The purpose of this Oklahoma State University/U.S. Army Mobility Equipment Research and Development Command research effort is to develop a new test and evaluation method for the contaminant sensitivity of fluid power pressure relief valves. This report contains the background research, test development, and test verification results which were conducted during the contract period. Also included is the proposed SAE standard procedure for relief valve contaminant sensitivity verification which has been developed. Finally, a new rating method for the contaminant sensitivity of relief valves is presented.

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Abrasive Wear						
Contaminant Lock						
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Pilot-Operated Relief Valves						
Contaminant Tolerance Profile						
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ASSESSMENT AND RATING OF THE CONTAMINANT SENSITIVITY OF RELIEF VALVES

FINAL REPORT

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PREFACE

This report presents a detailed account of the project activities concerning the relief valve contaminant sensitivity study. Included is the background, development, and presentation of the new proposed SAE standard test procedure for the contaminant sensitivity evaluation of relief valves. Also included is the presentation of a new rating system for the contaminant sensitivity of relief valves. Verification test data is included to reinforce the credibility of the new evaluation techniques which has been developed.

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CHAPTER I

SCOPE, PURPOSE, AND PLAN OF ATTACK

Due to the vital importance of overload protection in all hydraulic systems, the failure or malfunction of pressure relief valves should be guarded against. In order to insure the reliability of a pressure relief valve, such valves should be chosen according to stringent specifications and ratings. In particular, the contaminant sensitivity of pressure relief valves should be a characteristic highly respected. However, because of the absence of an industrially acceptable relief valve contaminant sensitivity evaluation technique, this crucial concept has largely been neglected.

The scope of this study was to develop an assessment and rating technique for the contaminant sensitivity of fluid power pressure relief valves. The results of this study would therefore be the development of:

1. A qualified contaminant sensitivity test procedure.
2. An evaluation technique to analyze data generated with this procedure.
3. A rating system which could be used for direct comparison purposes and which could be used to specify filtration requirements.
4. The ability to predict the life of a relief valve given any field contaminant level and duty cycle.

The plan of attack used to accomplish the scope of this study was to:

1. Investigate all of the modes of failure to which pressure relief valves are susceptible.
2. Investigate and evaluate all previously used contaminant sensitivity assessment procedures for relief valves.
3. Develop alternative test and evaluation techniques.
4. Using the preceeding information, develop a new test and evaluation technique.
5. Develop a computer program to process laboratory data into the desired information.
6. Summarize and compare the contaminant sensitivity of the major designs of relief valves.

CHAPTER II

THE MECHANISMS OF PERFORMANCE DEGRADATION IN RELIEF VALVES

As with all other type fluid power valves, the performance of pressure relief valves is adversely affected by particulate contaminants entrained in the working fluid. The degree to which each individual valve is affected is referred to as its contaminant sensitivity. For relief valves, there are two basic modes by which performance degradation due to contaminant can occur: contaminant lock and contaminant wear.

As is the case with directional control valves, if relief valves are allowed to remain idle in a contaminated environment for long periods of time, the pressure regulating poppets and spools can become "silted" by contaminant particles lodging in the clearances between the spool and the valve housing. If silting does occur, the spools become jammed or unable to move, thus creating the condition of a total loss of pressure relief capability. Even though this is potentially the most catastrophic form of relief valve failure, the likelihood of contaminant lock occurring in a moderately clean environment is very small.

Considering the other mode of relief valve degradation, contaminant wear effects are less drastic than the results of contaminant lock; however, the mechanism of contaminant wear is constantly working despite even a moderately clean environment. Because the condition of a perfectly clean fluid in the field is unrealistic, contaminant wear is a process which cannot be eliminated, only retarded. As severe as this statement might seem, the effects of contaminant wear in relief valves

can, however, be reduced to an insignificant level given the proper protection. From this discussion, it should thus be apparent that of the two modes of failure to be guarded against, performance degradation due to contaminant wear should be recognized to pose the most serious threat to the reliable operation of relief valves.

Therefore, considering the phenomenon of contaminant wear in more detail, it has been verified that the wear process in relief valves can be divided into two general categories; erosive wear and three body abrasive wear. These two forms of contaminant wear are illustrated in Figs. [2-1] and [2-2]. Both are the direct result of leakage flow and relief flow past the initial stage of a relief valve. These flows are therefore the mechanism by which contaminants are transported into the valve. As shown in Fig. [2-1], erosive wear occurs as the result of contaminant particles striking a surface and rebounding, disapating a portion of their energy into the surface in the form of strain energy. As is the condition in relief valves, this cycle is continuously repeated until the bombarded surface is strained past its elastic limit. At this point, each additional occurrence results in erosion of the surface. From physical observations, it has been verified that for the poppet section of relief valves, the erosion process eventually results in the "washing away" of one particular side of the poppet. This can be explained by the fact that erosion is a self-perpetuating process. Once an area is initially eroded, a "least resistance" flow path is formed, thus gradually channeling more contaminant-laden fluid through that particular area.

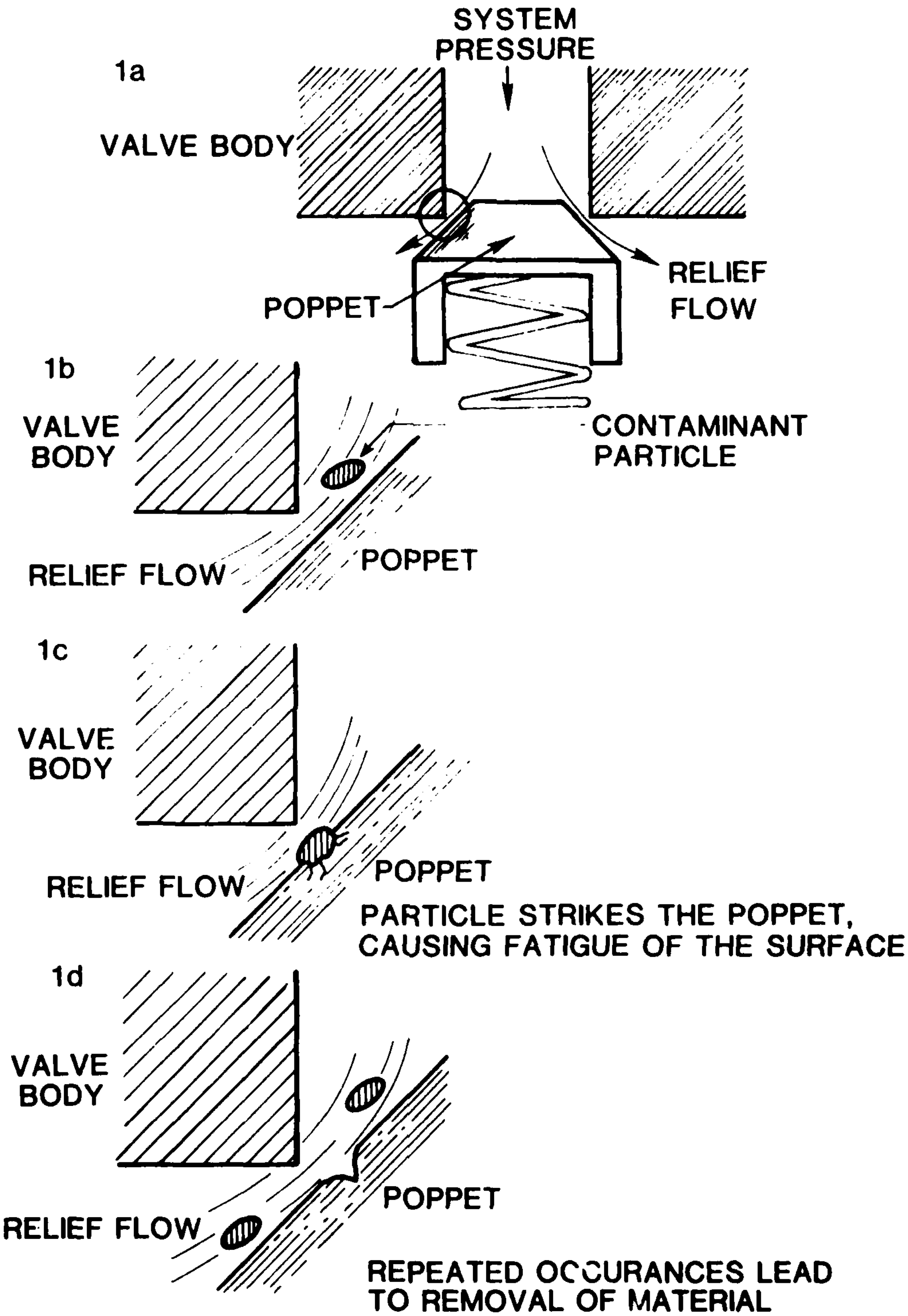


Illustration of Erosive Wear in Relief Valves.

Fig. 2-1 Illustration of Erosive Wear in Relief Valves

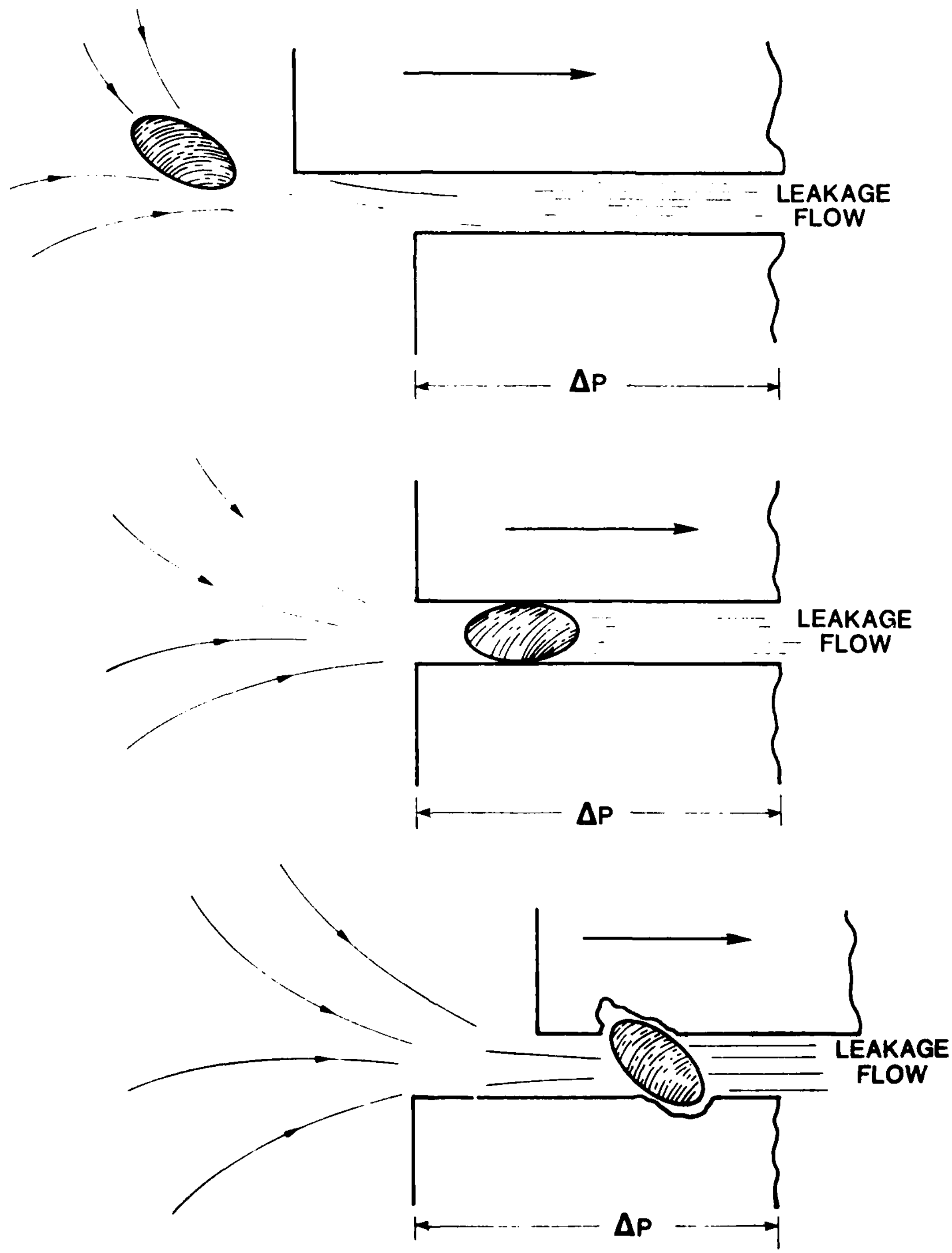


Fig. 2-2 Illustration of 3-Body Abrasive Wear

Considering the other mode of contaminant wear, three-body abrasive wear occurs whenever particulate contaminants become trapped between two moving surfaces, Fig. [2-2]. Again referring to the case of the poppet section of a relief valve, in its regulating state, the poppet is continually moving back and forth, seating and reseating against the control orifice as necessary to maintain the desired system pressure. Each time the poppet reseats, there is a possibility that as the two mating surfaces come into contact, contaminant particles are caught between the two. Depending on the makeup of the contaminant, either the valve surfaces are yielded or the particle is destroyed. In both occurences, however, the surface of the poppet and control orifice are left impaired. Abrasive wear is also capable of affecting the control piston of the main relief section of pilot-operated relief valves. For this occurence, the pressure differential across the piston applies the driving force necessary for leakage flow around the perimeter of the piston. As with contaminant lock, particles are carried into the annulus between the piston and valve body. This leakage flow can transport enough contaminant particles into the clearance that three body abrasion can occur. Abrasive wear in this area would consequently result in increased amounts of leakage flows past the piston.

Of the two modes of contaminant wear discussed, the degree to which each occur in excess of the other has not been determined. Thus, the report will henceforth utilize the term "contaminant wear" to

include both mechanisms of relief valve performance degradation.

The results of contaminant wear in relief valves can be observed by physical performance degradations which occur. The most obvious performance change is the alteration of cracking and reseating pressures. The cracking pressure is that at which the valve poppet is forced off its seat, thus initiating the pressure relief sequence of the valve. The reseating pressure is that at which the poppet will return to its seat, thus completing the pressure relief sequence. The change in these two performance parameters can be attributed to the "new positioning" of the poppet which is present after contaminant wear has occured. Once material has been worn away in the critical area of the poppet section (the area where the poppet and control orifice touch) the return spring of the valve gradually advances the poppet further into the control orifice until it again reseats. This subsequently exposes more surface area of the poppet to the pressurized fluid field. The increased area creates a larger force on the poppet than was present for the same system pressure before wear. As the result of this increased force, the cracking pressure of a relief valve can be drastically reduced. Because the valve now cracks at a lower pressure, the initial pressure setting of the valve is lost. In this case, system pressure can be restored only by either readjustment or replacement of the valve. Contaminant wear on the poppet also causes a decrease in the reseating pressure of a relief valve. This decrease results in longer periods of time required for the valve to complete its pressure relief sequence. This again can present several unwanted problems.

The second major performance change due to contaminant wear in relief valves is that associated with the pressure versus flow characteristics of the valve. As the physical shape of the poppet or piston is changed due to wear, the flow forces acting upon them are also changed. This results in a characteristic alteration of the shape of the pressure/flow profile of the valve.

Thus, the conclusions which can be drawn from the discussions presented in this chapter are:

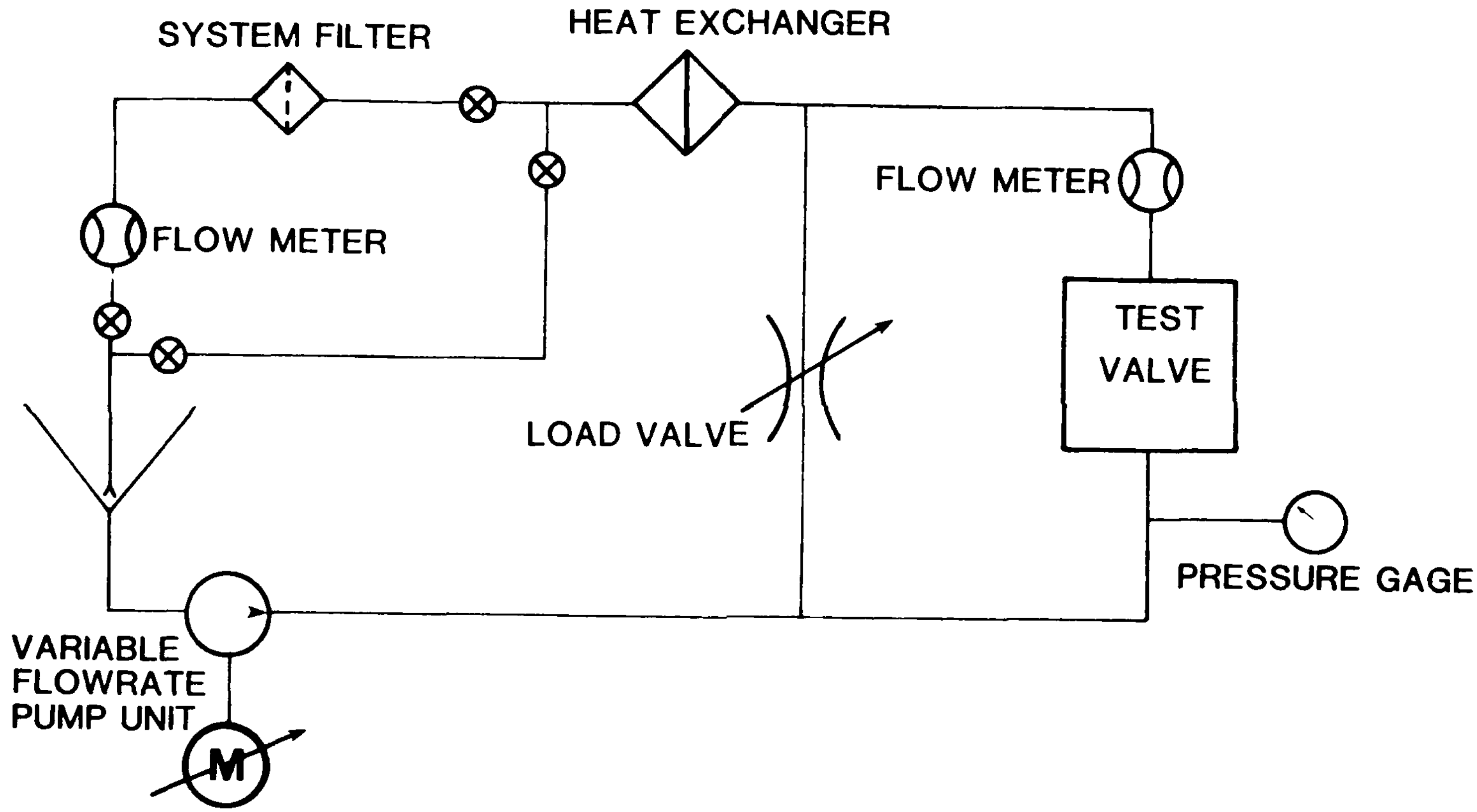
1. Of the two prevalent modes of contaminant sensitivity to which pressure relief valves are susceptible, contaminant wear presents the greatest threat to the normal operation of this component.
2. Three major performance parameters cracking pressure, reseating pressure, and the pressure versus flow characteristic-are altered due to contaminant wear.

CHAPTER III

INVESTIGATION AND ASSESSMENT OF EXISTING RELIEF VALVE CONTAMINANT SENSITIVITY TEST AND EVALUATION TECHNIQUES

For this research study, it was felt that in order to optimize the development of a new evaluation technique for the contaminat sensitivity of relief valves, a complete review of all existing evaluation methods should be conducted. From this review, the faults and deficiencies which the existing techniques exhibit could be avoided in the new procedure. Also, a foundation for the new procedure could be based on the positive attributes of the existing procedures. Therefore, this chapter deals exclusively with the discussion of the two basic philosophies which have been utilized to test relief valves--static testing and dynamic testing. Each method will be examined in two parts--test procedure and data interpretation technique.

It should first be noted that the titles given to both procedures are descriptive of the manner in which the relief valve being tested is operated during these periods of time in which contaminant is maintained in the test system. Therefore, for the static test, the test valve is maintained at one static operating condition for the duration of the test. Whereas for the dynamic test, the test valve is exposed to a cyclic operating condition. The static test uses a circuit such as that illustrated in Fig. [3-1]. This circuit was designed to simulate the working cycle of pressure relief valves. For both techniques, by completely closing the needle valve in the circuit, all flow could



Relief Valve Contaminant Sensitivity Test Circuit–Static Test.

Fig. 3-1 Relief Valve Contaminant Sensitivity Test Circuit-Static Test

be directed through the test valve. The static test procedure simply calls for the injection of a set amount of classified contaminant (AC Fine Test Dust) into the test circuit. After 30 minutes of exposure to the contaminanted fluid, the system is filtered and the cracking pressure of the valve recorded. This degraded cracking pressure is then compared to the initial cracking pressure of the valve. This process is repeated for gradually increasing contaminant particle sizes. Termination of this test occurs if this performance parameter degrades to seventy-percent of the initial value. The test flowrate was arbitrarily chosen to be one-half the maximum rate value for the valve. Data derived from this test is then manipulated into a value referred to as the contaminant sensitivity index (CSI). After computing the percent performance parameter degradation for each contaminant size range is then summed to yield the contaminant sensitivity index for the test valve. This value is then used for comparison with other relief valves tested in a like manner. The above procedure has also been followed utilizing the reseating pressure as the observed performance parameter. Typical test results from the above procedure are shown in Figs. [3-2] and [3-3].

Making a general assessment of the static evaluation technique, although the basic concepts on which the test procedure are based are sound in their approach, it fails to justify its choice of certain test conditions, specifically, the test flowrate and the time allowed for contaminant injection. This selection was apparently the result of a satisfaction with a "comparative approach", on the part of the test

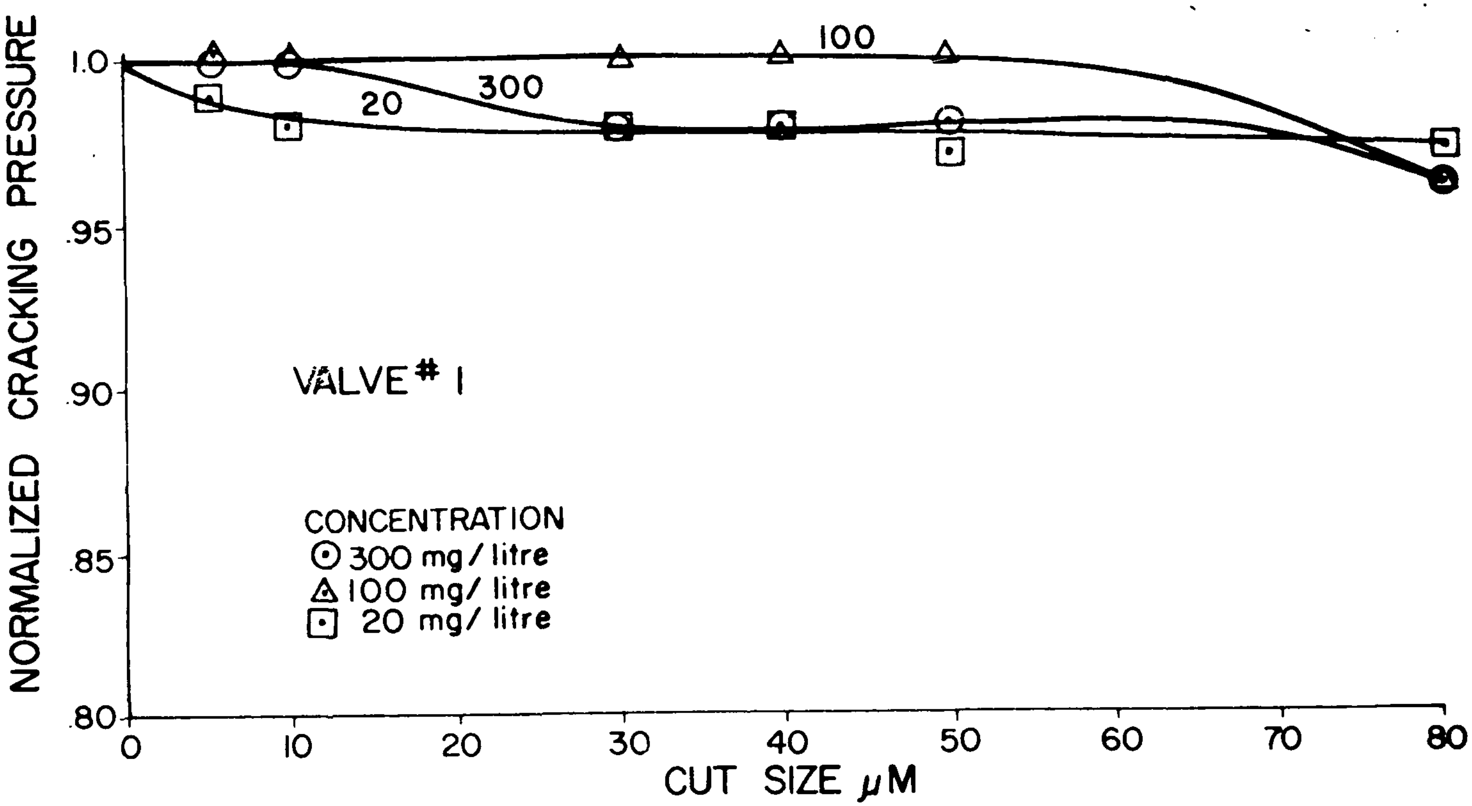


Fig. 3-2 Example of the Cracking Pressure Degradation Versus Contaminant Size

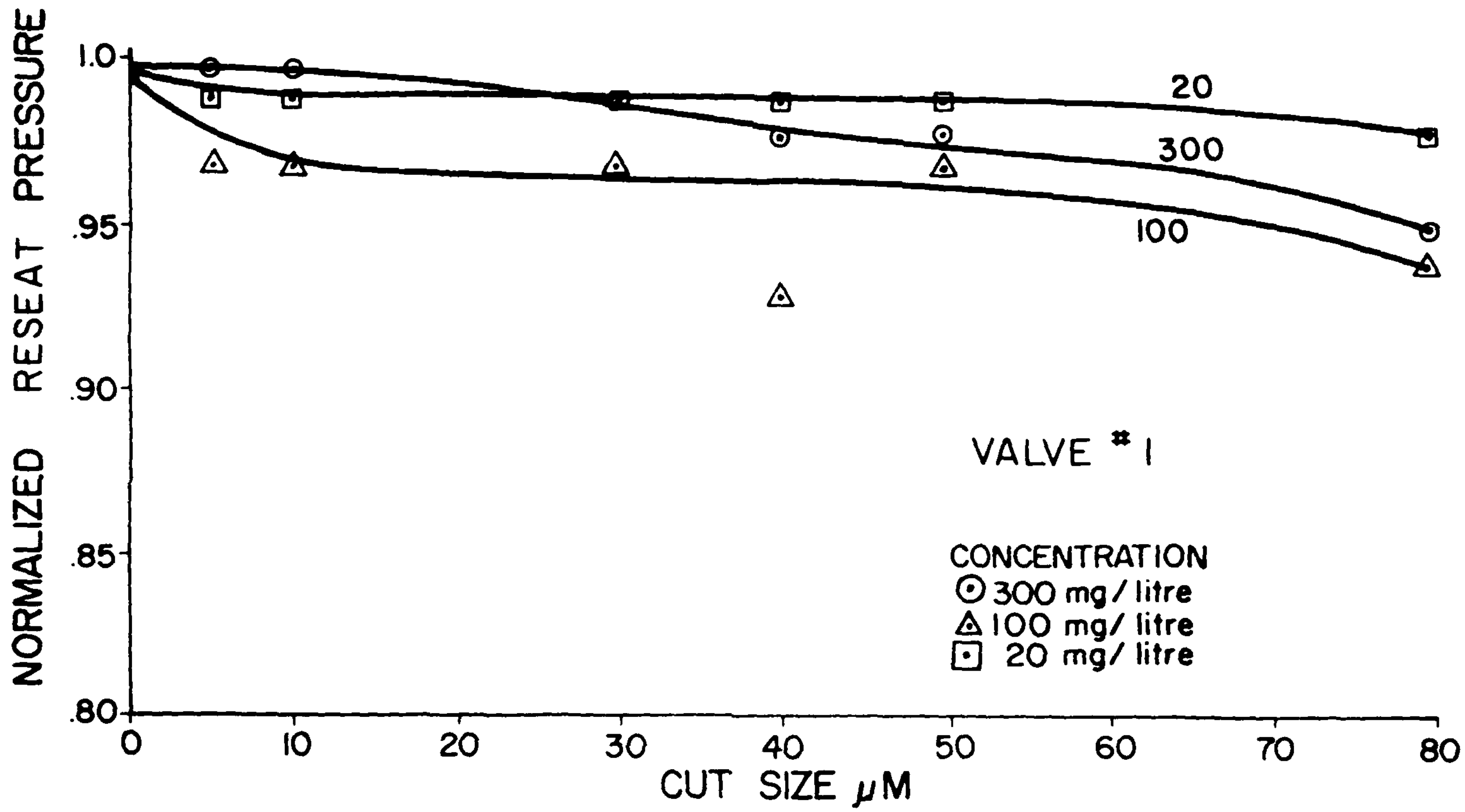


Fig. 3-3 Example of the Reseating Pressure Degradation Versus Contaminant Size

originators. Also, a weakness which has been determined to be the single largest handicap to the reliability of the test is the selection of the cracking or reseating pressure as the observed performance parameter. Although these pressures are vital performance characteristics, test data have proven the inconsistency which they incorporate into the procedure. This is basically due to the nature of events which are occurring during the observation of the cracking or reseating pressure. At this point, the valve is at its "threshold" region of operation. It is undergoing the change from a passive system element to an active pressure regulating system element. The final deficiency of the static evaluation technique is the test data interpretation method which it follows. The rating index (CSI) which is derived is simply a manipulation of numbers without any theoretical basis. This aspect alone shows the static approach to be grossly obsolete in today's technologically advanced world. It is therefore strongly recommended that this data evaluation technique be avoided in any future data compilation methods.

Bearing a strong resemblance to the static evaluation technique, the dynamic approach differs only in the actual test conditions under which the test valve is operated. Whereas the static test maintains constant system operating parameters during the contaminant injection, the dynamic test exposes the test valve to a cyclic pressure condition. The test circuit is identical to the static test circuit except for the cyclic flow input device in the dynamic circuit Fig. [3-4]. The rationale for conducting the test in this manner is to simulate field

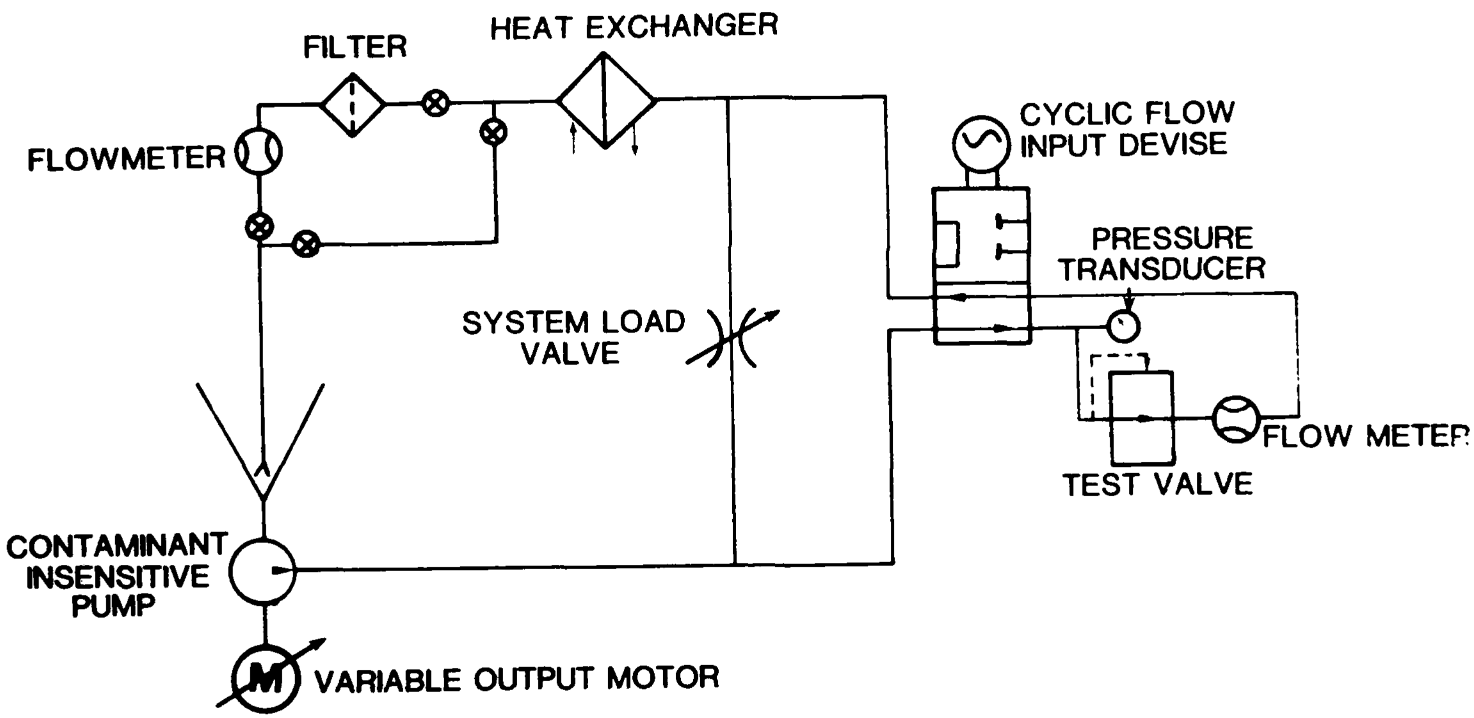


Fig. 3-4 Relief Valve Contaminant Sensitivity Test
Circuit-Dynamic Test

conditions. Because actual field operation involves unavoidable pressure surges which cause system relief valves to crack, this test method could generate degradation data which are closer to actual field degradation levels. The test flowrate and contaminant injection scheme are the same as the static test. Observed performance parameters are also the same. Typical test data are shown in Fig. [3-5]. If these similarities were not enough, the dynamic procedure also utilizes the CSI data evaluation technique.

Even though the concept of a dynamic test condition is justified, the idea of having a device which could vary its flow input frequency to accurately simulate field conditions is unrealistic. As concluded by Foord and Tessmann [1] in a previous relief valve contaminant sensitivity study, the effects of a dynamic test are much less severe than static test degradation. This is attributed to the "actual" amount of time during which sensitive areas of the valve are exposed to contamination. For example, if the test valve were cycled at 30 cycles per minute, the exposure rate during dynamic testing would be less than 25% of that for the static test. Subsequently, the valve should only wear 25% of that amount which would occur during a static test. This statement thus validates the assumption that of the two modes of contaminant wear possible in relief valves, erosion effects are apparently much more detrimental than any abrasion action which might occur. Thus, from this point forth, performance degradation in relief valves will be assumed to mainly result from erosive wear. This assumption does not exclude abrasive wear effects, but considers them negligible when

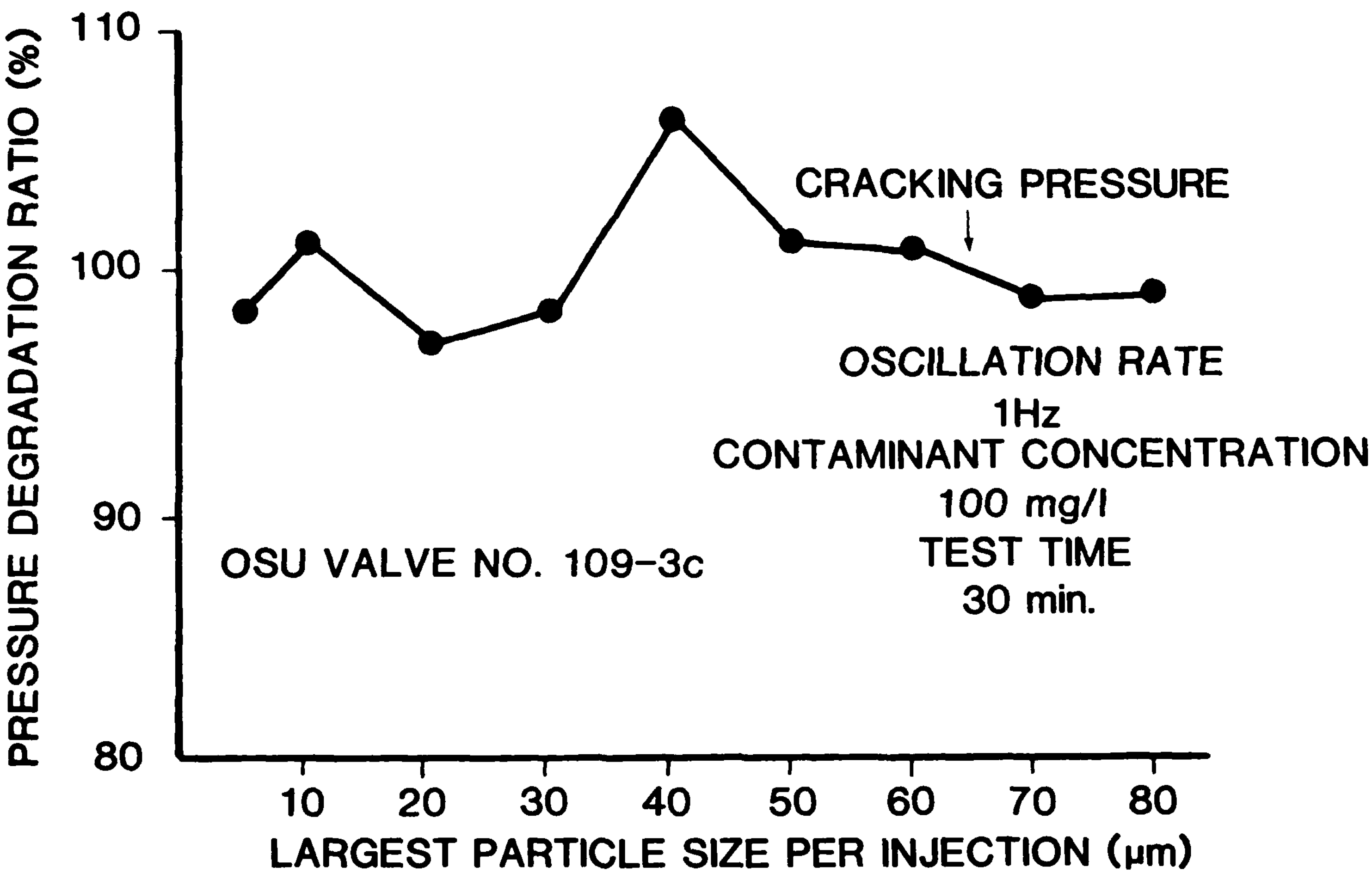


Fig. 3-5 Dynamic Test Results

compared to erosion effects.

Therefore, considering the poor data interpretation technique which it utilizes, it has been concluded that the dynamic evaluation technique should be discontinued. It should be noted, that although the consideration of field duty cycle effects on the degradation of relief valves is a very important concept, it is felt that its effects can be accounted for elsewhere in a data evaluation method.

Summarizing the insights gained from this investigation, the new test procedure should choose its test parameters using a theoretically justified selection process. Secondly, a new performance degradation parameter should be determined, and finally, a pressure relief valve contaminant sensitivity theory must be developed. In general, although the existing test methods are basically sound, they lack the theoretical insights which are requisite for a reliable accelerated degradation test.

CHAPTER IV

POSSIBLE ALTERNATE TEST AND EVALUATION TECHNIQUES

With the valuable insight gained from the review of all presently used relief valve contaminant sensitivity test and evaluation techniques, it was possible to optimize the development of new contingencies for this purpose. Keeping in mind the inadequacies of the present methods, several new alternatives were conceived. Although the data selection and interpretation techniques are unique for each, the actual test procedure which they follow is basically the same. Of eight alternatives initially considered, five were selected as candidates for more in-depth study. These five can be categorized into two basic classes according to the performance parameter which is observed in each. They are the static performance degradation and the dynamic performance degradation. These names should not be confused with the static and dynamic testing procedures. This usage of the words; static and dynamic, refers to post degradation performance characteristics. In other words, the static performance degradation approach considers those performance parameters which can be monitored while the test valve is in a static operating mode. The dynamic performance degradation approach, on the other hand, monitors those performance parameters which are related to the dynamic response characteristics of the relief valve. The data acquisition techniques which the static approach includes are pressure/flow degradation analysis and degradation rate analysis. The latter technique is further composed of two approaches, pressure decrease rates and relief-flow increase rates. The dynamic

approach is also comprised of two techniques; step-input response degradation analysis and frequency response degradation analysis. All the above mentioned data acquisition techniques will be discussed individually in more detail following a discussion of the previously mentioned test procedure which each will utilize.

As recommended in Chapter III, a new contaminant sensitivity test procedure should justify its choice of test conditions. Therefore, consideration was given to the development of a theory by which to select these parameters. The approach which was derived is based on the simple fact that pressure relief valve performance degradation is directly proportional to the amounts of relief flow which pass through the valve. Also, considering that the basic motive of all contaminant sensitivity tests is to accelerate the performance degradation of the test component, this is enhanced with relief valves by operating them at their most severe conditions. For relief valves, this would be the condition when the maximum rated flow of the test valve is passing through the component. Thus, for all the proposed alternative procedures, this would be the standard test flowrate. Because this flowrate simulates the most severe case, the degradation data which would be generated using this parameter would also represent the most severe degradation possible for a valve. Since this is not an accurate representation of the majority of field applications, it would be erroneous to claim field life using this raw data alone; however, if duty cycle considerations were added to this approach, the real field

life could be predicted. Thus from extreme laboratory degradation data, less severe field degradation can be interpolated to any user's application. This consideration greatly enhances the value of test data generated using the maximum rated flowrate for the test valve.

Also neglected in the present test procedures was the justification of actual testing time. The 30 min. time period for exposure to contaminant was not based on any particular rationale. Therefore, it was decided that test time would be set at the amount of time necessary for relief valves to exhibit a specific degradation tendency. This value would necessarily be selected only after many experimental tests.

Thus, with the exception of the above test parameters, the remainder of the new proposed test procedure would closely resemble the previously described static test procedure. Hereafter, the new test will be referred to as the "modified static test". The data acquisition techniques which were proposed to be used in conjunction with the "modified static test" will be discussed in detail below.

PRESSURE/FLOW DEGRADATION ANALYSIS

As discussed earlier in Chapter II, the result of erosive wear on the sensitive areas of relief valves can be observed by the characteristic alteration of the pressure/flow profile of the relief valve. As a valve is worn by the contaminant, the pressure/flow "signature" of the valve has been observed to deviate from the original profile, Fig. [4-1]. The extent to which this "signature" is affected can be considered to indicate a relief valve's contaminant sensitivity. This

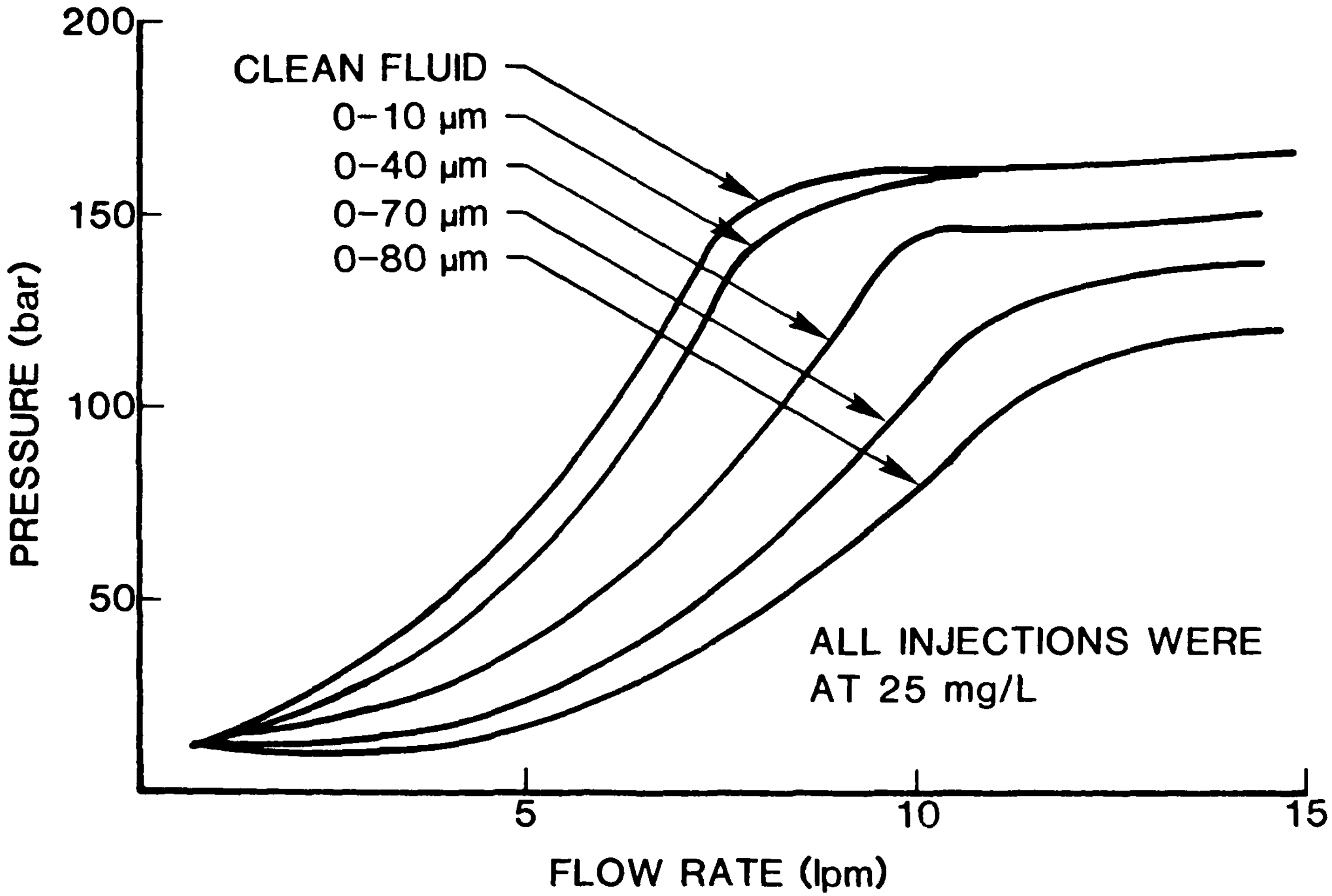


Fig. 4-1 Pressure/Flow Degradation Due to Contaminant Wear for OSU Valve No. 113–1.

technique thus requires the monitoring and recording, on hard copy, of the pressure/flow profile of the test relief valve before and after contaminant wear. Using the test circuit shown earlier in Fig. [3-1] this profile is easily generated by utilizing pressure and flowrate transducers in conjunction with an X-Y plotter. Each profile derived after a contaminant injection is then compared to the initial pressure/flow profile and a percent change calculated. The exact location of the point to be monitored was dependent upon the results of experimental tests to determine the most consistently sensitive portion of the pressure/flow profile for several test valves. (This experimental verification will be discussed later.) This point, which would be determined, would thus be standardized in much the same way as the cracking and reseating pressures were previously standardized in the static test procedure.

DEGRADATION RATE ANALYSIS

Due to the fact that all relief valves are constructed differently, the rate at which internal parts are eroded due to contaminant is an individual characteristic of all valves. More specifically, the wear rates for different size contaminant particles would also be unique for all valves. This subsequently results in characteristic performance degradation rates which all relief valves exhibit. Thus, performance degradation rates as a result of contaminant wear can be utilized as the criteria by which to compare the contaminant sensitivity of relief valves.

As presented earlier, it has been verified that the pressure/flow signature of a relief valve is altered as a result of contaminant wear effects. In the majority of cases observed, maintaining a constant relief-flow through the test valve during a period of exposure to contamination resulted in a noticeable decrease in the system pressure which the test valve can maintain. Fig. [4-2]. Conversely, maintaining a constant system pressure resulted in an increase in relief-flow rates. Fig. [4-3]. Thus these two types of degradation can be considered as the performance parameters to observe. Therefore, the data aquisition procedure would consist of either of two approaches, pressure degradation rate analysis or relief-flow increase rate analysis.

For the pressure degradation rate analysis, the test valve would be exposed to contamination while constantly maintaining the maximum rated relief flow through it. During this period of exposure, the system pressure would be constantly recorded. This process is repeated for several different size ranges of classified test contaminants. From plots of system pressure vs exposure time, the degradation rates for each size injection can be determined. Those values can then be used for comparison with other valves tested in the same manner. Also from this degradation rate information, field life can be predicted.

Considering the relief-flow increase rate analysis, the initial pressure at the valve's maximum rated flow is the pressure level maintained for all contaminant injections during the test. For this technique, during the contaminant exposure periods, the relief flowrate

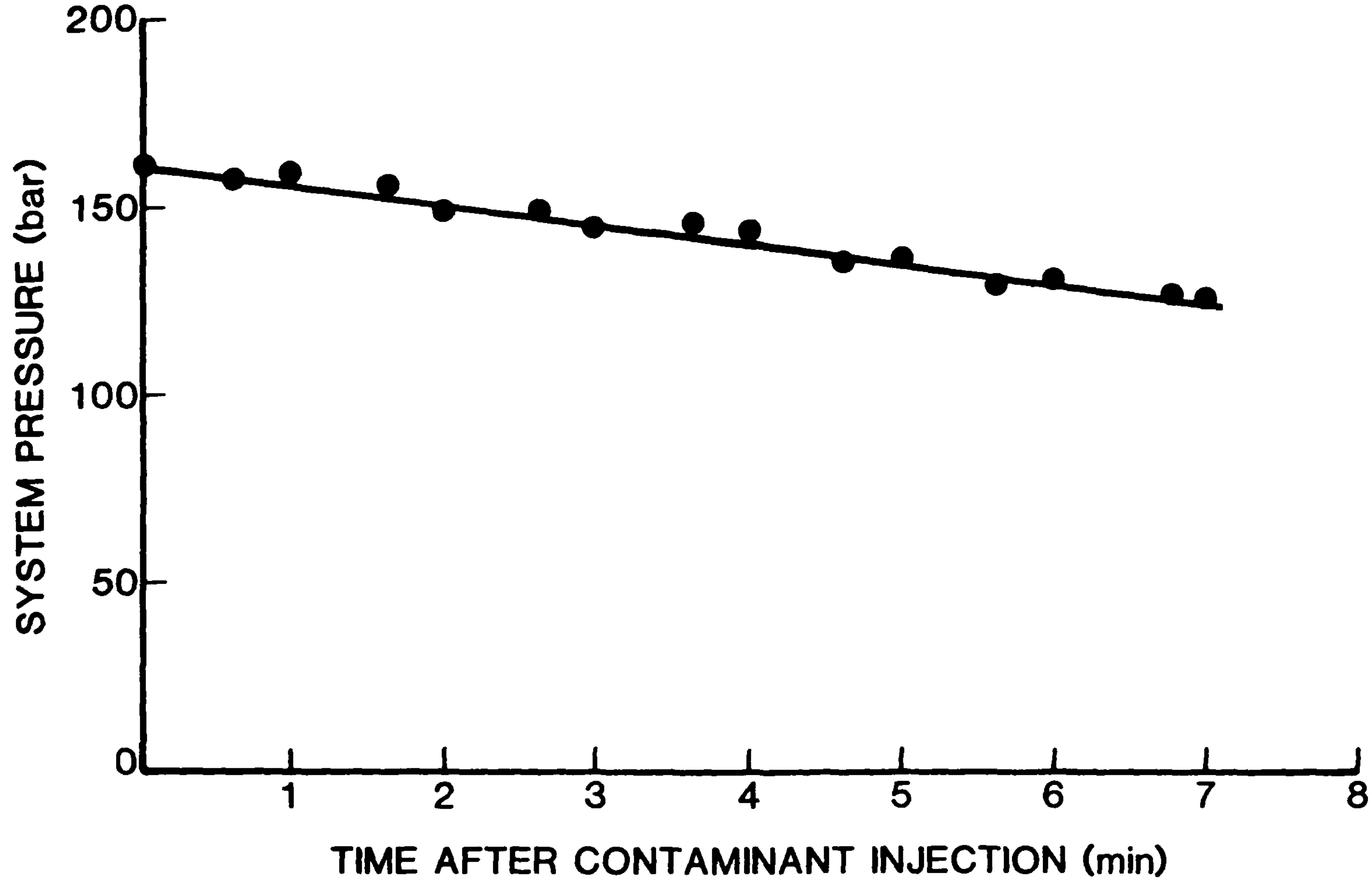


Fig. 4-2 Example of Pressure Decrease Due to Contaminant Wear

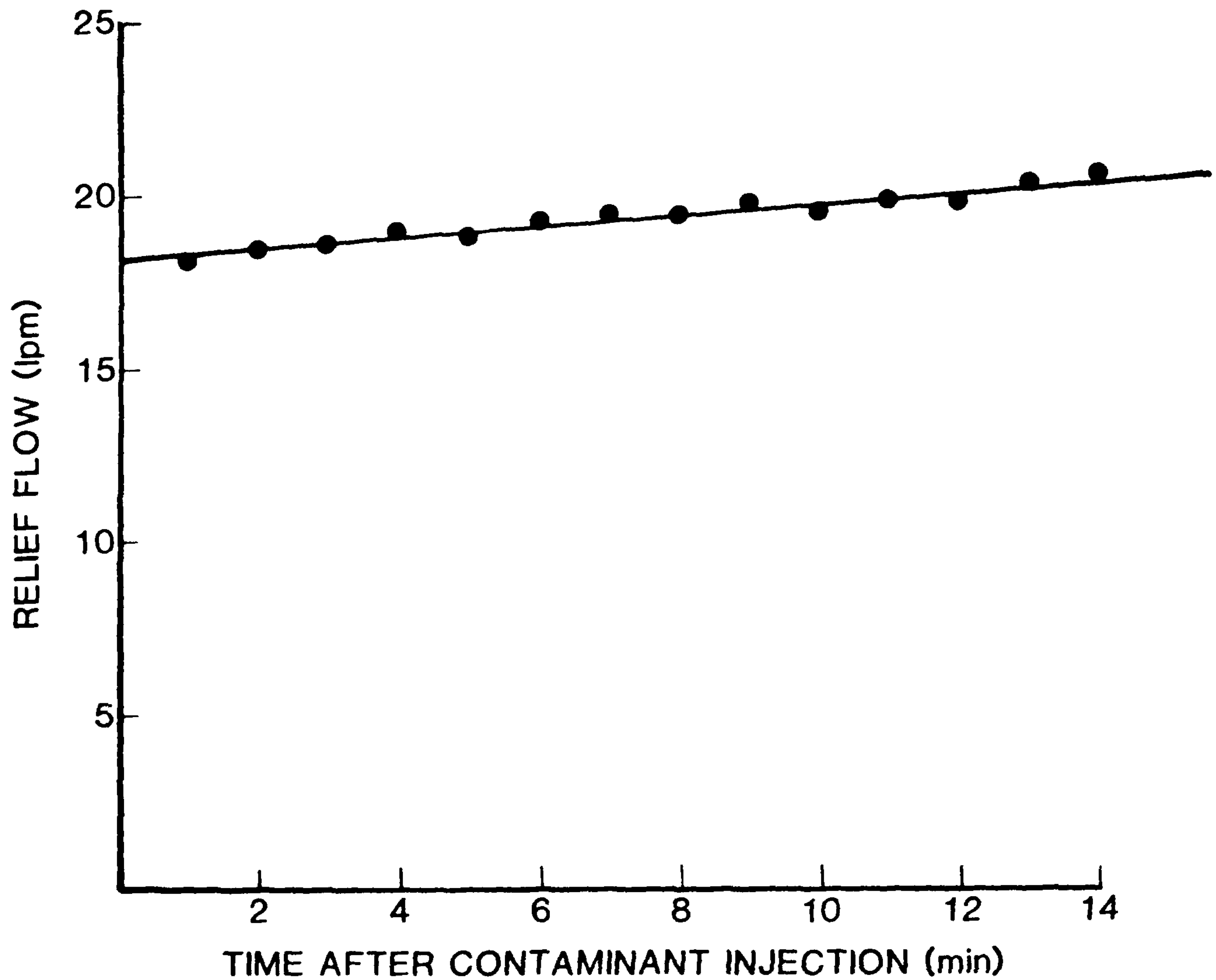


Fig. 4-3 Example of Relief Flow Increase Due to Contaminant Wear

is constantly recorded. In the same manner as with pressure degradation rates, the rate of increase of relief flow as a function of time can be derived for each contaminant size range injection. Also, given a prescribed level of relief flow which is unacceptable, the life of the relief valve can be predicted.

DYNAMIC RESPONSE DEGRADATION

One characteristic of all physical systems is the manner in which each responds to a forced input. When this characteristic is considered in a time based analysis, this property is referred to as the dynamic response of the system. This property can be further divided into two more specific categories--step response and frequency response. The step response is merely the manner in which a system reacts to a sudden, or step, input. The frequency response is the manner in which a system reacts to a series of inputs, whether cyclic or a succession of step inputs. Both approaches utilize specific performance parameters to assess the dynamic response of the system. Because pressure relief valves are merely a combination of several physical elements (springs, masses, dampers) they can be considered as simple mechanical systems. Therefore, since all systems are different, the dynamic response is a characteristic which would be unique in all aspects.

As discussed in Chapter II, sensitive areas of relief valves are eroded away as the result of fluid contamination. This removal of material thus changes the shape and mass of those sensitive areas. It is therefore reasonable to expect the dynamic response character-

istics of a relief valve to be altered as a result of contaminant wear. Just as with degradation rates and pressure/flow profile changes, the degree to which the dynamic response is affected is characteristicly unique for all relief valves. Thus, this type performance characteristic can be utilized in a contaminant sensitivity evolution procedure.

First considering the step input response analysis, by applying a step pressure input to the valve and recording the resultant system pressure, such characteristics as percent overshoot, rise time, delay time, and settling time can be observed. From this observation, an important parameter in system control theory known as the damping coefficient can be derived. This quantity is simply a measure of the ability of a system to check the vibration or oscillation of the system. Thus, using the modified static test as described earlier as the means to expose the test valve to contaminant, followed by the examination of the step response characteristics in clean fluid, this procedure would generate data that would accurately represent the contaminant sensitivity of the valve. Fig. [4-4].

Now considering the frequency response analysis, following exposure to contaminant by the modified static test procedure, the relief valve is subjected to cyclic pressure inputs of varying frequency. At each observed frequency, the system pressure which is maintained is monitored and recorded. As shown in Fig. [4-5], the relief pressure of a valve will decrease as the frequency of inputs increases. This is the result of the configuration of which relief valves are composed.

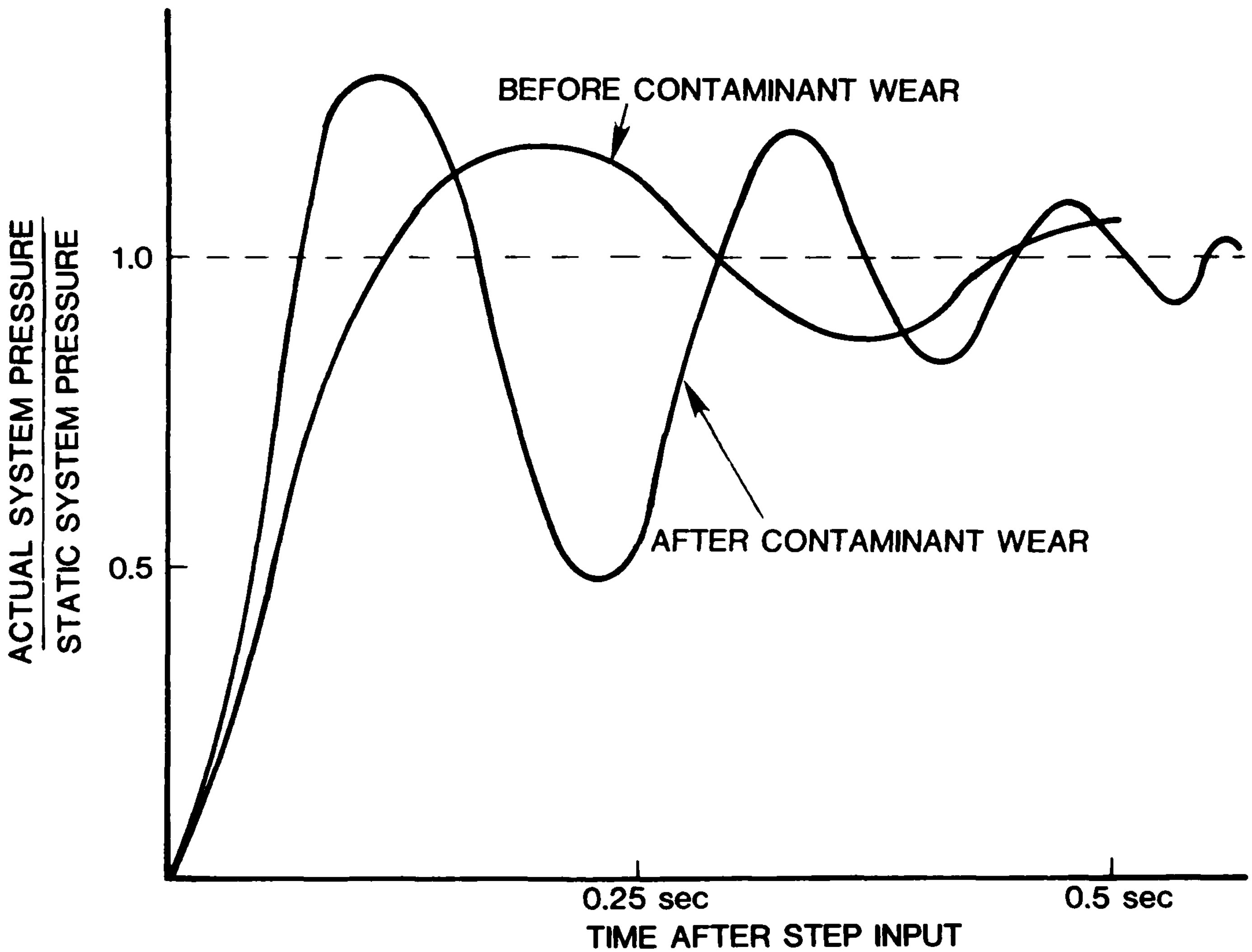


Fig. 4-4 Step-Response Characteristics

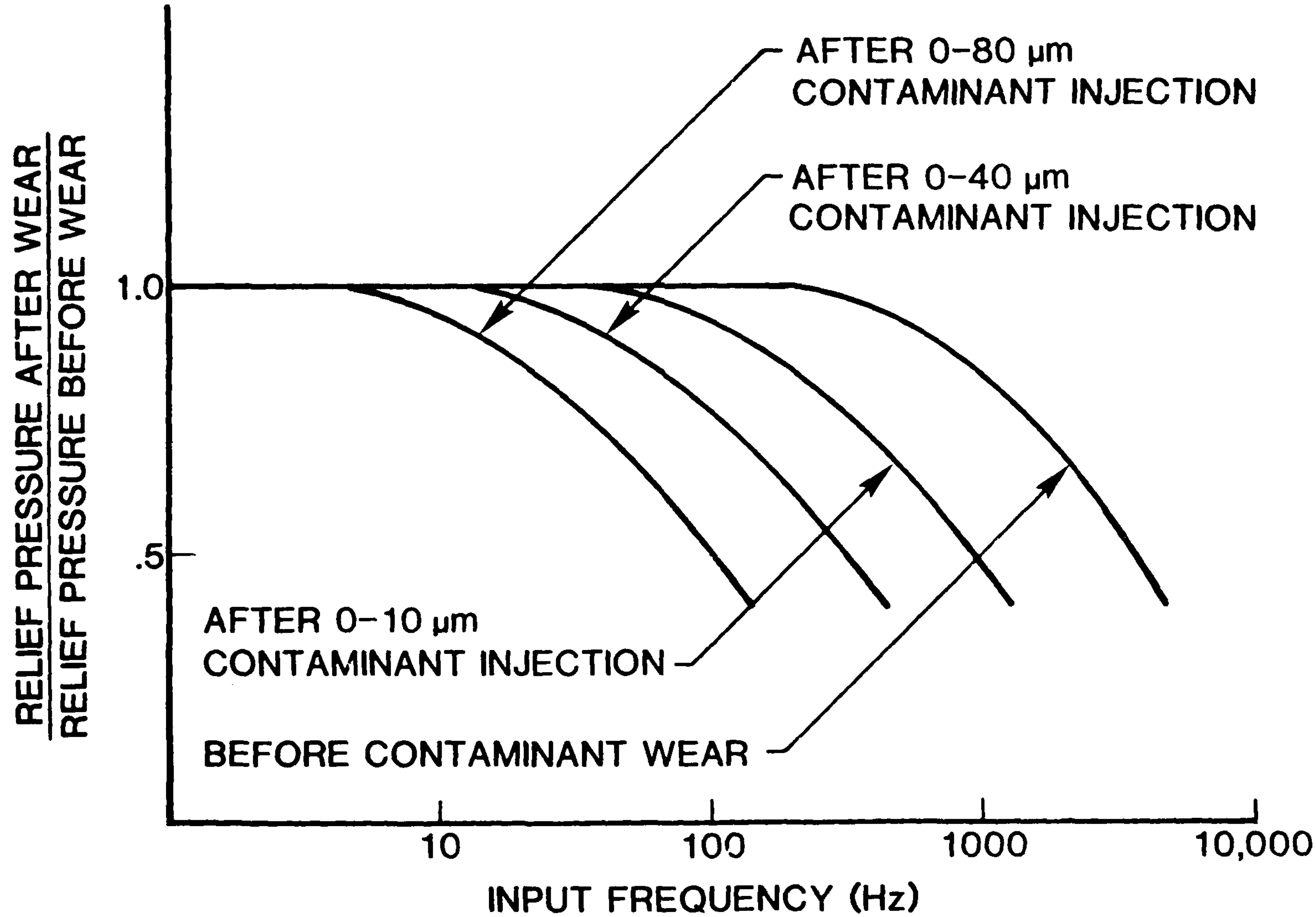


Fig. 4-5 Frequency Response Characteristics

As discussed earlier, a relief valve can be thought of as a mechanical system composed of spring, mass, and damping elements Fig. [4-6]. This system is essentially considered as a second-order system. The response of this order system is directly related to the damping coefficient. For such systems, the magnitude of the damping coefficient is determined by the combination of all it's constituent mechanical elements. Finally, the stability of these systems is controlled by this parameter. If the damping coefficient is decreased, the stability is also decreased, and vice versa if the damping coefficient is increased. This instability results in over amplification of forced inputs to the system. In other words, if under static conditions, an input of magnitude, F, causes an output of magnitude, x. For the same magnitude of input but at a cyclic frequency of occurence, the output magnitude will increase. In the case of relief valves, the input can be thought of as the force applied to the poppet or spool due to system pressure. The actual output is the movement of these parts which all relief valves rely on to relieve excessive system pressure. Because this movement is directly observable as the relief pressure of the valve, the output of this system can be thought of as the relief pressure. Thus if a cyclic input is applied to a relief valve, the force required to initiate movement of the poppet or spool toward it's relief position is reduced. Therefore, for relief valves, the result of a cyclic pressure field is a decrease in the relief pressure of the valve. The precise frequency response of relief valves is therefore a performance characteristic which is also unique for all

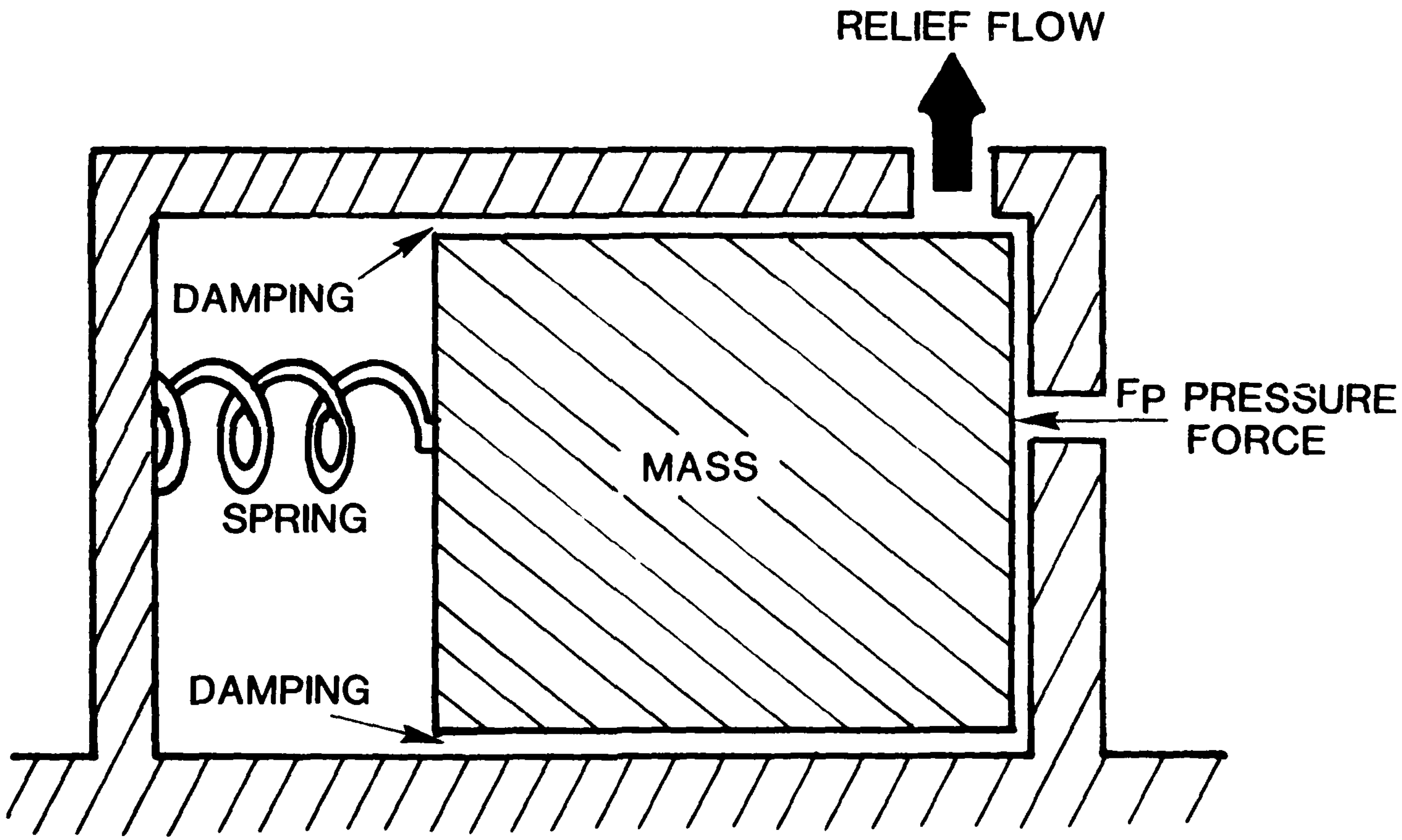


Fig. 4-6 System Model of a Direct-Acting Pressure Relief Valve

valves. Since sensitive areas of relief valves are eroded due to contamination, the magnitudes of the masses and damping of the system will be changed. This will subsequently change the frequency response of the valve. A combination of this degradation data selection technique and the modified static test procedure would present a very discriminating method to analyze the contaminant sensitivity of pressure relief valves. Again, this data would be considered using a degradation theory in order to predict field life.

Summarizing, contaminant sensitivity assessment procedures can be considered to be comprised of three separate analyses; test procedure, data aquisition, and data interpretation. Each part contributes equally to the quality of the assessment procedure as a whole. This chapter has presented alternatives to the test procedure and data aquisition in an attempt to upgrade the present techniques. The revised test procedure discussed and the five data aquisition analyses described are certainly capable of increasing the reliability and discrimination of degradation data over the present techniques. Thus, all that remains in the development of an entirely new assessment procedure is the selection of one of the five data aquisition approaches and the development of a relief valve performance degradation theory to interpret this data. Both of these areas are covered in the subsequent chapters.

CHAPTER V

SELECTION OF A NEW TEST AND EVALUATION TECHNIQUE

Selection of a Test Method

After considering the alternative data aquisition techniques presented in Chapter IV, it was evident that all were acceptable as standard procedures. Thus, selecting only one of these required consideration of the actual feasibility to accomplish the evaluation set forth in each.

The frequency response degradation analysis requires a variation in the frequency of pressure inputs to the test valve. Because the frequencies which would be required are very high and would need to be variable, the requirement to construct such a versatile high speed actuator would be both expensive and difficult. This consideration eliminated the frequency response analysis as a feasible method.

For the step-input analysis, a high-speed measurement instrument would be required in order to "catch" the very quick response of most relief valves. The speed requirement of this kind of instrumentation is beyond the X-Y recorder which is usually used in industry, thus not feasible for standardized testing.

Of the variations of the static performance analysis which were considered, the pressure/flow profile degradation analysis was chosen as the best alternative. This decision was based on the basic ideal which this procedure follows. This procedure was superior to the

degradation rates analysis by being better suited for interfacing with a relief valve performance degradation theory. The amount of instrumentation required to conduct this analysis is either less than or the same as all the other techniques. For the pressure/flow degradation analysis, all that is required is a contaminant insensitive flow measuring device and a pressure measuring device. These two components were also a requisite for the other analysis techniques. Thus, with this basic approach in mind, a series of experimental tests were conducted to optimize and formalize the exact set of steps which would be followed.

Experimental Tests

As mentioned during the discussion of the pressure/flow degradation analysis in Chapter Iv, in order to simplify the analysis of this technique, a single coordinate on the pressure/flow profile should be determined with which to evaluate performance degradation. This point would be chosen as that which consistently illustrates the highest degree of degradation as a result of contaminant wear effects. This point would then be the standard by which to evaluate all relief valve's sensitivity to contaminant.

In order to determine the most sensitive point, experimental tests were conducted. The experimental test procedure which was followed was similar to the modified static test introduced earlier. This procedure produces the maximum rate of performance degradation possible for the test valve.

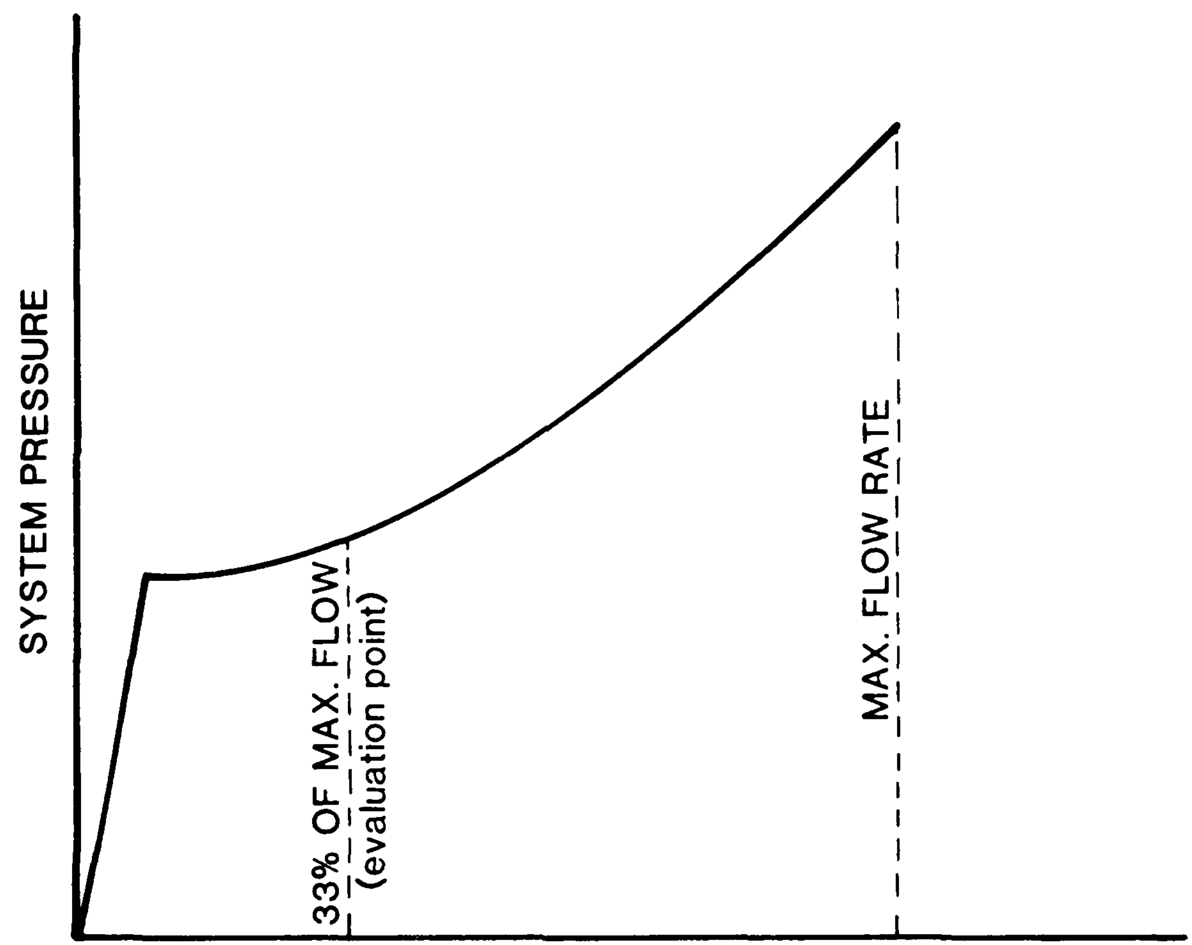
Therefore, operating at their maximum rated flow, 16 relief valves were tested. Each test consisted of 30 minute periods of running, using discrete size ranges of AC Fine Test Dust including 0-5, 0-10, 0-20, 0-30, 0-40, 0-50, 0-60, 0-70, and 0-80μm. With the information gained from these tests, the location of the most sensitive point could be determined. After a period of break-in, or until the test valve exhibited consistent operating characteristics in clean fluid, the pressure/flow profile of the test valve was recorded by X-Y plotter. This recording was repeated following filtration after each contaminant injection period. An example of the pressure/flow degradation which occurs in a pilot-operated relief valve was shown in Fig. [4-1]. Evaluation of the degradation of various points along the pressure/flow profile for each test valve resulted in the identification of the most consistently sensitive point.

In order to adequately describe this operating point, the mechanism by which relief valves operate should be clearly understood. For direct-acting relief valves, pressure is sensed by the force which is applied to the poppet or spool exposed to the system pressure. This poppet or spool is held in position by a spring. As system pressure increases, the spring deflects, allowing for movement of the poppet or spool. System pressure is relieved whenever the poppet or spool is displaced to the point at which the relief orifice is opened so that fluid can pass directly through the valve to the return lines of the system. At this condition, if the system pressure increases further, the amount of flow which passes through the valve will increase. The

pressure versus flow characteristics which result follows the orifice equation relationship, Fig. [5-1].

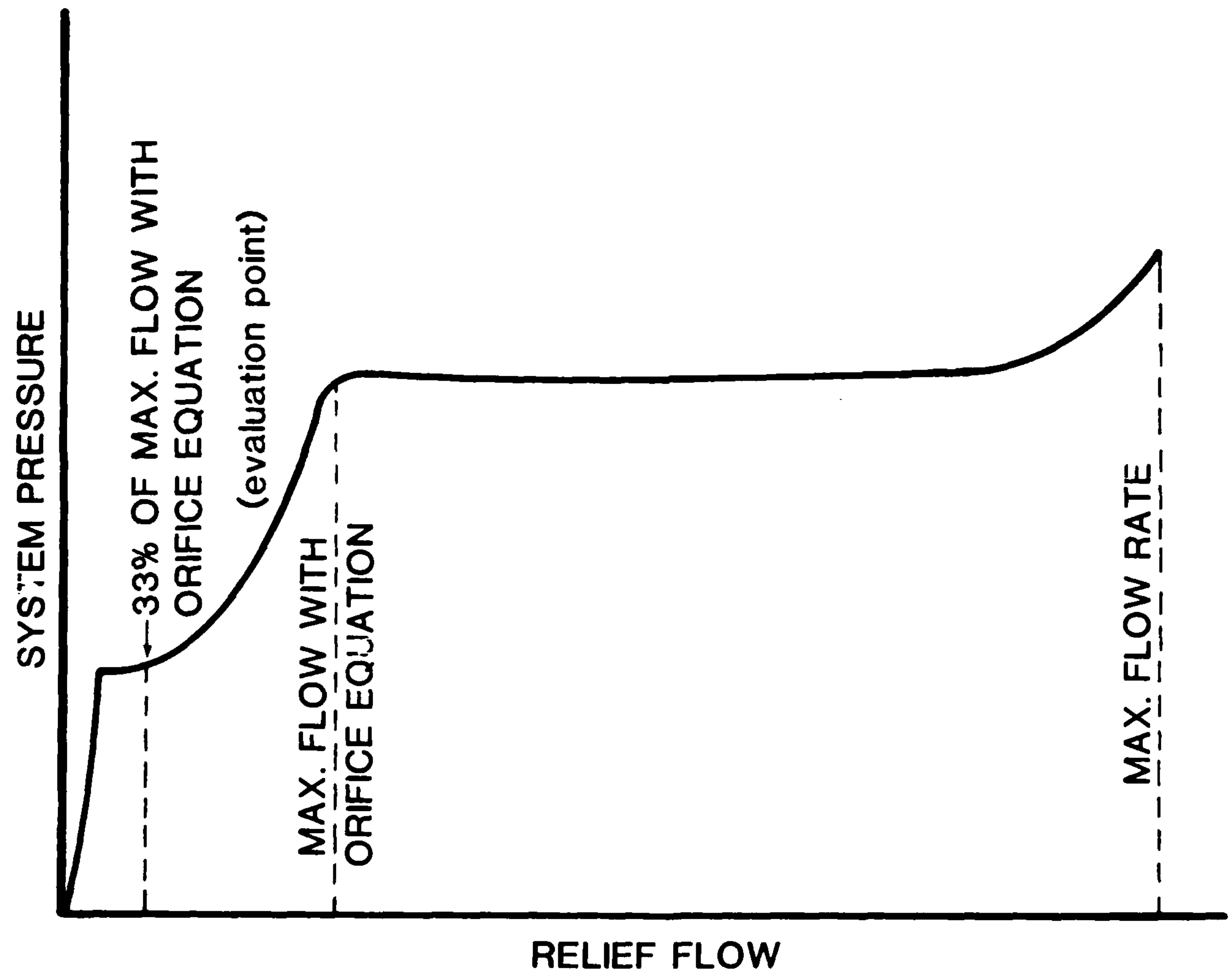
Pilot-operated relief valves are sometimes referred to as two-stage relief valves. The first, or pilot, stage is essentially a direct-acting relief valve which is used to activate the second, or main, stage of the valve. The main stage takes over the pressure regulation after the pilot stage has been activated. Thus, for pilot-operated relief valves, the pressure versus flow characteristic generally consists of two regions. The region controlled by the pilot section in some instances results in the orifice equation relationship similar to direct acting relief valves. The second stage generally maintains a stable pressure level until relief flow increases to the point that the valve acts again as a simple orifice. The two basic shapes of the pressure/flow profile for pilot-operated relief valves are shown in Fig. [5-2], [5-3].

Continuing the earlier discussion, it has been verified by experiment that for both direct-acting and pilot-operated relief valves, the pressure at 33% of the maximum flow in the region exhibiting the orifice equation relationship tended to be consistently more sensitive to contaminant wear than any other point along the curve. Fig. [5-4] shows some typical test data which led to the selection of this point. For pilot-operated relief valves which did not exhibit the orifice equation relationship of Fig. [5-3], the point at 33% of the maximum rated flow showed as much consistent degradation as any other point.



Typical Direct-Acting Relief Valve Pressure/Flow Profile.

Fig. 5-1 Pressure/Flow Characteristics of a Typical Direct-Acting Relief Valve



Typical Pilot-Operated Relief Valve Pressure/Flow Profile.

Fig. 5-2 Pressure/Flow Characteristics of a Typical Pilot-Operated Relief Valve

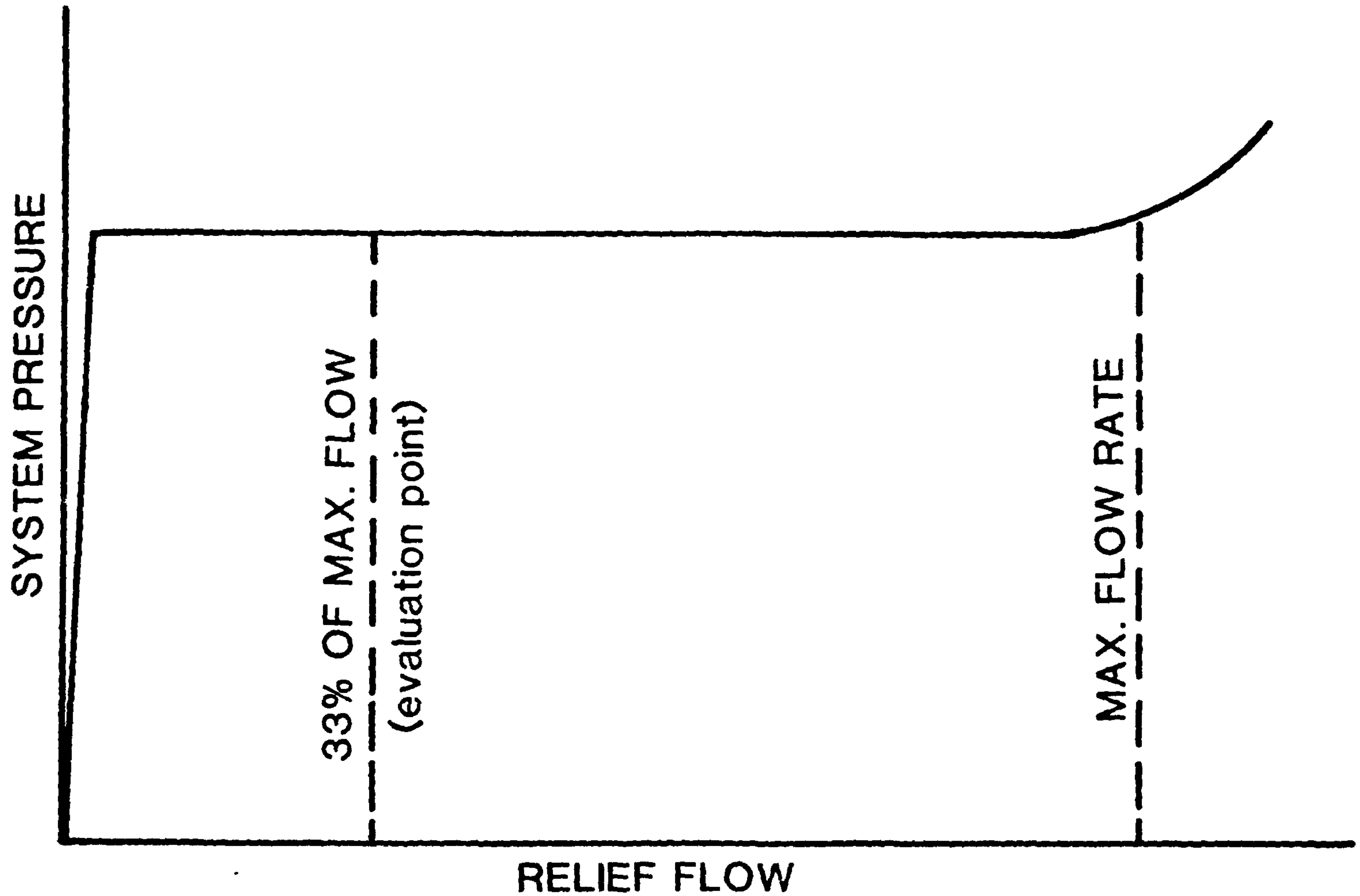
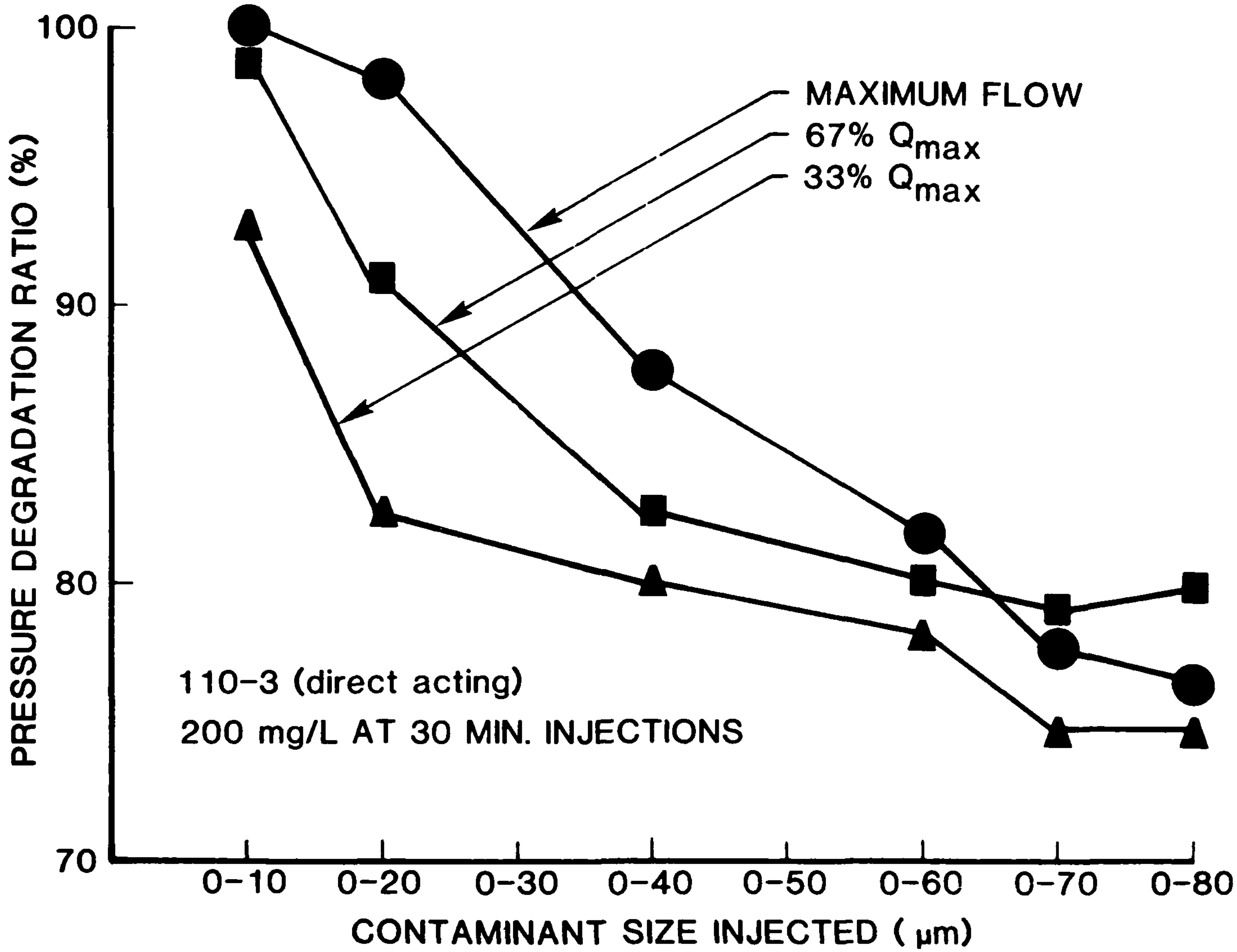


Fig. 5-3 Pressure/Flow Characteristics of a Typical Pilot-Operated Relief Valve



Pressure Degradation at Various Points Along the Pressure/Flow Curve.

Fig. 5-4 Pressure Degradation at Various Points Along the Pressure/Flow Curve

Thus, the recommended data aquisition point shall be the pressure at the following flow rates:

1. For direct-acting relief valves, 33% of the maximum rated flow for the valve. Fig. [5-1].
2. Pilot-operated relief valves with orifice characteristics, 33% of the maximum flow in the region governed by the orifice equation relationship. Fig. [5-2].
3. Pilot-operated relief valves without orifice characteristics, 33% of the maximum rated flow for the valve. Fig. [5-3].

With the above, a common parameter by which to evaluate otherwise dissimilar system components is now available. This can be used as a standard with which to observe and monitor the contaminant sensitivity of pressure relief valves. Therefore, the development of a new data aquisition technique is complete.

Further refining the actual test procedure with which to generate degradation data required optimizing test time and test contaminant concentration. As stated in Chapter III, the optimum time of exposure to contaminant should be determined by actual tests on the degradation rate which relief valves experience. The test time would be chosen as that which would allow the test valve to degrade to the point that any further performance degradation could be predicted from the preceding degradation. Thus, open examining the degradation rates for all the relief valves which have been experimented with, it was determined that the majority of the performance degradation which occurred during a contaminant injection did so within 15 minutes from the time

of injection. Although in some cases the time was less than 15 minutes, in all instances, it never exceeded this time. Therefore, the standard test procedure should call for the circulation of test contaminants for a period of 15 minutes, after which the system fluid would be filtered.

The selection of the test contaminant concentration (mg/ℓ) was also based on experimental verification. In all test valves evaluated, excessive contamination levels (200-300mg/ℓ) resulted in erratic performance of the valve during contaminant exposure periods. This was explained to be the result of contaminant silting of the valve (contaminant lock). Contaminant lock of the control poppet is prevented by the continuous movement of the poppet disallowing the silt to build up to a critical level. What resulted was a sluggish movement restriction placed on t' poppet. This subsequently led to erratic pressure surges to the system. Also, adequate filtration of the system fluid and complete purging of the test valve of contaminant was hampered by the excessive test concentration levels.

For concentrations of 25-100 mg/ℓ, contaminant lock effects were not evident. Therefore, in order to avoid unwanted pressure increases and to expedite test valve clean up, high contaminant concentration levels were deemed undesirable as test standards for relief valves. Thus, 100 mg/ℓ is the optimum contaminant concentration to avoid contaminant lock effects yet achieve accelerated performance degradation. Thus, the standard test procedure should utilize AC Fine Test Dust in the concentration of 100 mg/ℓ.

Standard Test Procedure

Combining the above procedures and parameters, the RELIEF VALVE CONTAMINANT SENSITIVITY TEST AND DATA AQUISITION TECHNIQUE is as follows:

METHOD OF MEASURING AND REPORTING THE CONTAMINANT SENSITIVITY OF HYDRAULIC PRESSURE RELIEF VALVES

1. Purpose

   To provide a uniform procedure for evaluating the contaminant sensitivity of fluid power relief valves.

2. Scope

   This recommended practice applies to all hydraulic pressure relief valves which maintain or limit the pressure in the system.

3. Terms & Definitions

   3.1 Test flow - any steady state flowrate required to conduct the test.

   3.2 Test pressure - the pressure drop across the test valve.

   3.3 Relief flow - the amount of flow which passes through the test valve during a period of pressure regulation.

   3.4 Relief pressure - the pressure maintained by the test valve at a particular relief flow.

   3.5 Pressure/Flow Profile - a plot of the relief pressure vs relief flow characteristic of the test valve.

   3.6 Maximum rated flow - the maximum amount of relief flow through the test valve as specified by the manufacturer.

   3.7 Maximum rated pressure - the relief pressure at the maximum rated flow unless otherwise specified.

   3.8 Pressure degradation - any change in relief pressure due to contaminant effects.

   3.9 Reference flow - the relief flow at which pressure degradation

is measured.

3.10 Reference pressure - the relief pressure at the reference flow.

3.11 Contaminant injection - refers to the act of introducing classified test contaminants to the system fluid.

3.12 Test duration - the amount of time after each contaminant injection in which the test valve is exposed to contaminanted fluid.

3.13 Contamination concentration - the contaminant weight per unit volume of fluid.

4. Units

4.1 The International System of Units (SI) is used herein in accordance with Reference paragraph (15.5).

4.2 Approximate conversion to U.S. units appear in parenthesis after SI units.

5. Graphic Symbols

Graphic symbols used herein are in accordance with Reference paragraphs (15.2) and (15.3). Where References (15.2) and (15.3) are not in agreement, Reference (15.2) governs.

6. Summary of Designated Information

6.1 Specify the following information on all requests for this test:

6.1.1 A full description of the valve.

6.1.2 The type of fluid.

6.1.3 The fluid temperature if different from (7.1).

6.1.4 The test pressure.

6.1.5 The test flow rate.

6.1.6 The test contaminant if different from (7.3).

7. <u>Test Conditions</u>

7.1 Fluid Temperature - shall be 65°C (150°F).

7.2 System Volume - shall be numerically equal to one half the maximum rated flow per minute of the test valve as recommended by the manufacturer.

7.3 Test Contaminant - Classified AC Fine Test Dust, 0-5μm, 0-10μm, 20μm, 30μm, 40μm, 50μm, 60μm, 70μm, and 80μm, which are produced AC Fine Test Dust per Reference (15.6).

7.4 Test Contaminant Concentration - 100 mg/ℓ.

7.5 Test flow - the maximum rated flow for the test valve.

7.6 Test pressure - the maximum rated pressure for the test valve.

7.7 Initial cleanliness level - the contaminant concentration level of the circulating fluid shall be less than 10 mg/ℓ.

8. <u>Test Condition Accuracy</u>

Maintain the test condition accuracy within the limits shown in Table 1.

TABLE 1

TEST CONDITION	MAINTAIN WITHIN ±
FLOW	2%
PRESSURE	2%
TEMPERATURE	2°C (3.6°F)
CONTAMINANT CONCENTRATION	10%

9. Letter Symbols

The following symbols are used in this document:

Q_{MAX} - maximum rated flow

P_{MAX} - maximum rated pressure

Q_{REF} - reference flow rate

P_{REF} - reference pressure

Q - test flow

P - test pressure

10. Test Equipment

10.1 Hydraulic flow source insensitive to contaminant.

10.2 Clean-up filter capable of achieving the initial cleanliness level.

10.3 Heat exchanger which does not act as a contaminant trap.

10.4 Reservoir with a conical shaped bottom.

10.5 Flow diffuser at the point where the main return line empties into the reservoir.

10.6 Four-way valve to by-pass system filter during contaminant injection periods.

10.7 Needle valve to direct all flow through the test valve.

10.8 Flow measuring device which is insensitivie to contaminant.

10.9 Pressure sensing device.

10.10 Lines connecting hydraulic components sized so that turbulent mixing exists throughout.

10.11 Test circuit as shown in Fig. 1.

11. <u>Test System Qualifying Procedure</u>

11.1 Insert a direct connection in the test circuit in place of the test valve.

11.2 Adjust system volume so that it equals 45% to 55% of the minimum flow rate per minute at which the test system is intended to be used.

11.3 Circulate the fluid through the system filter until the contaminant background is less than 10 mg/ℓ.

11.4 By-pass the filter.

11.5 Add unclassified AC Fine Test Dust per Reference (15.6) to the fluid to bring the contamination concentration to 100 mg/ℓ.

11.6 Inject the contaminant of clause (11.5) in the form of a well-mixed slurry uniformly over a period of one minute.

11.7 Operate the system at the minimum flow rate as described in Clause (11.2).

11.8 Extract four fluid samples from the system per Reference

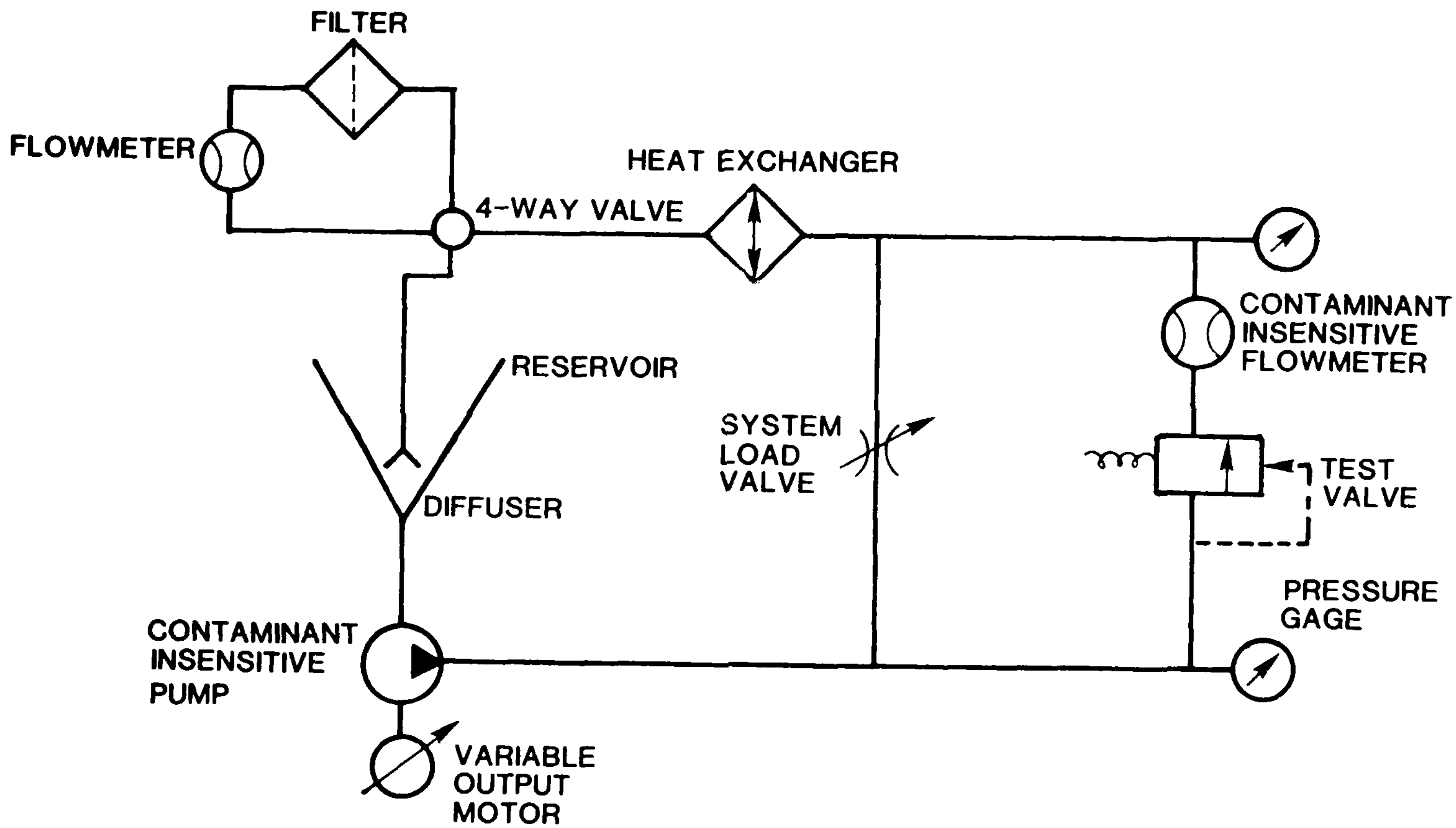


Fig. 1 Pressure Relief Valve Contaminant Sensitivity Test Circuit

(15.4) at 15 minute intervals from the completion of contaminant injection.

11.9 Measure the contaminant concentration level of each sample per per Reference (15.4).

11.10 Consider the system qualified for testing if the contaminant concentration levels of clause (11.9) are within ±10% of the initial requirement of clause (11.5).

11.11 Repeat this qualification procedure when any modification to the flow path or to the reservoir is made.

12. <u>Test Procedure</u>

12.1 Install the test valve into the test circuit, Fig. 1.

12.2 Filter the fluid until the contaminant concentration level is less than 10 mg/ℓ.

12.3 Subject the test valve to a period of break-in as follows:

12.3.1 Adjust the relief flow to be one-half Q_{MAX}, continue for a period of 30 minutes.

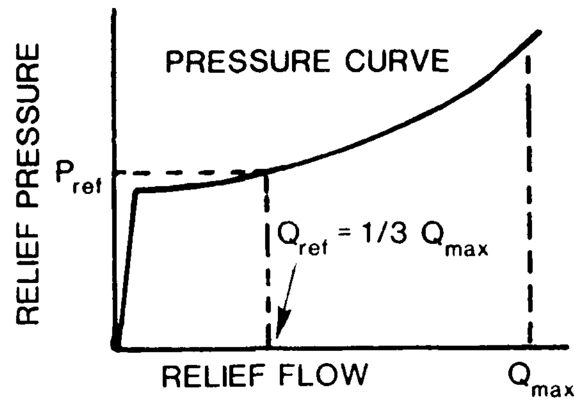
12.3.2 Adjust the relief flow to be Q_{MAX}, continue for a period of 30 minutes or until the relief pressure remains constant for 10 minutes.

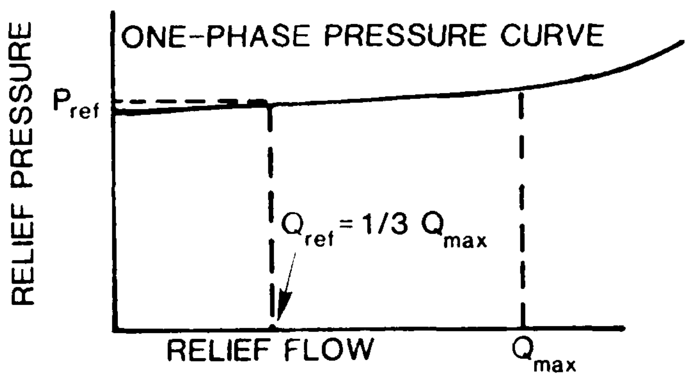
12.4 By-pass system filter.

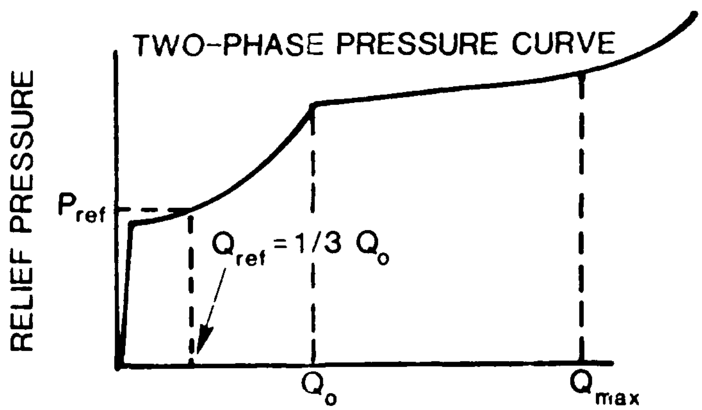
12.5 Record P_{REF} according to Q_{REF} as specified below:

12.5.1 For direct acting relief valves, Q_{REF} is as shown in Fig. 2.

12.5.2 For pilot operated relief valves, Q_{REF} is determined as shown in Fig. 3 and Fig. 4 depending upon the test valve.







Figs (2, 3, 4) Criteria for Reference Pressure Selection

12.6 Adjust flow to Q_{MAX} by gradually closing the system load valve.

12.7 Prepare a slurry of classified AC Fine Test Dust (0-5μm) which will bring the contaminant concentration level of the fluid up to 100 mg/ℓ.

12.8 Inject the slurry uniformly over a period of one minute.

12.9 Allow the contaminant to circulate through the test valve for a period of 15 minutes.

12.10 Completely open the system load valve to stop any relief flow through the test valve.

12.11 Filter the fluid until the contaminant concentration level is less than 10 mg/ℓ.

12.12 Repeat clauses (12.4) through (12.11) for contaminant sizes, 0-10μm, 0-20μm, 0-30μm, 0-40μm, 0-50μm, 0-60μm, 0-70μm, and 0-80μm.

13. <u>Data Preparation</u>

13.1 Record test valve identification, and operating conditions in Table 2.

13.2 Tabulate test data in Table 2.

13.3 Calculate the reference pressure degradation ratio to a maximum of three significant figures for each contaminant. injection by dividing the reference pressure after each injection by the initial reference pressure.

13.4 Plot on linear coordinates the pressure degradation ratios calculated in (13.3) versus the respective maximum particle

Table 2 Test Report Sheet

TEST REPORT SHEET

VALVE DESCRIPTION ______________________________

OSU VALVE No. ______________________________

TEST DATE ____________________

TYPE OF FLUID ______________________ FLUID TEMP. ________

TYPE OF CONTAMINANT ______________________________

GRAVIMETRIC LEVEL ______________________________

MAXIMUM RATED FLOW ______________________________

REFERENCE FLOWRATE ______________________________

INITIAL PRESSURE AT REFERENCE FLOWRATE ________________

CONTAMINANT SIZE (μm)	PRESSURE AT REFERENCE FLOWRATE AFTER INJECTION UNITS:
0-5	
0-10	
0-20	
0-30	
0-40	
0-50	
0-60	
0-70	
0-80	

size for each injection. (Example Fig. 5)

14. Identification Statement

Use the following statement in catalogs and sales literature when electing to comply with this voluntary standard; "Performance data obtained and presented in accordance with SAE practice_______."

15. References

15.1 American National Standard Glossary of Terms for Fluid Power, ANSI/893.2 - 1971.

15.2 International Standard Graphic Symbols for Hydraulic and Pneumatic Equipment and Accessories for Fluid Power Transmission, ISO/R, 1219-1970. Agrees with ANSI/Y32, 10-1967.

15.3 American National Standard Fluid Power Diagrams, ANSI/Y14, 14-17-1966.

15.4 Assessing cleanliness of Hydraulic Fluid Power Componentes and Systems - SAE J1227.

15.5 International Standard Rules for the Use of the International System of Units and a Selection of the Decimal Multiples and Sub-Multiples of S.I. Units, ISO/R, 1000-1969.

15.6 Air Cleaner Test Code - SAE J726C.

Using this test procedure, performance degradation data due to contaminant wear has been generated. Illustration of the discrimination possible with this procedure is shown in Fig. [5-5]. Data generated by this test procedure can subsequently be used in conjunction with the relief valve contaminant sensitivity computer program to determine the Omega rating of the valve which is a rating value for contaminant

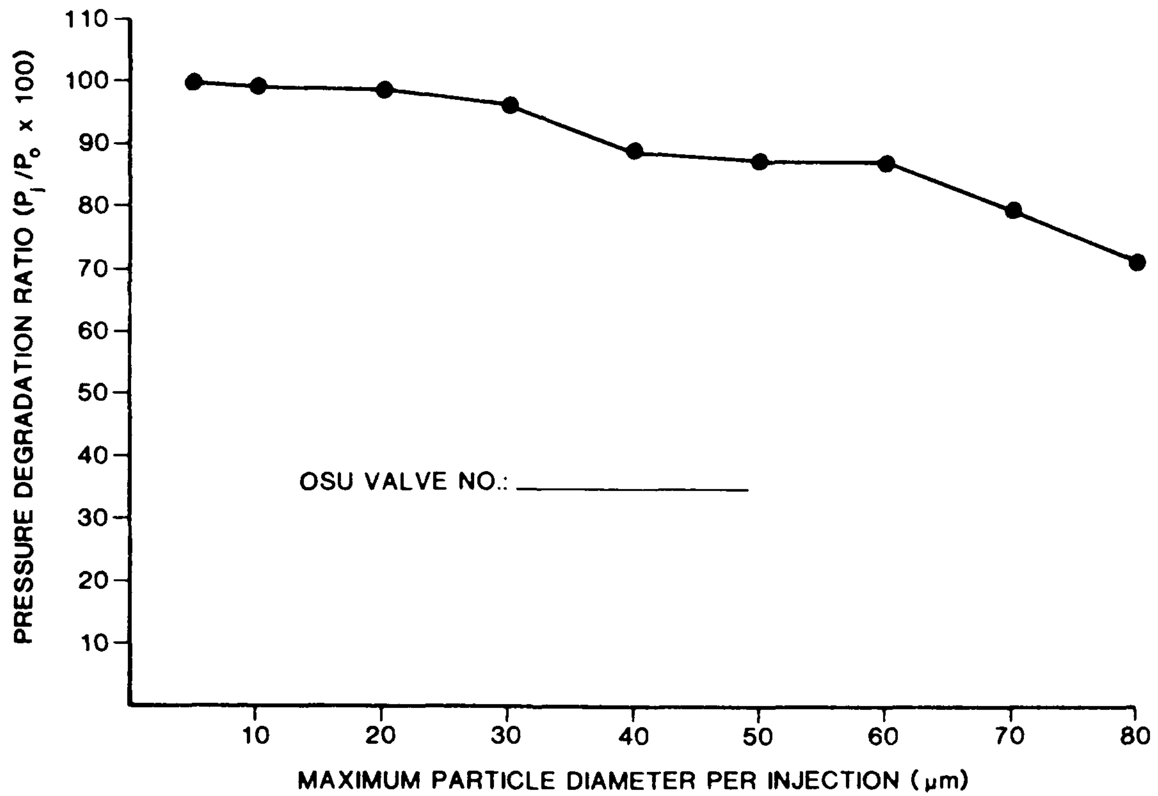
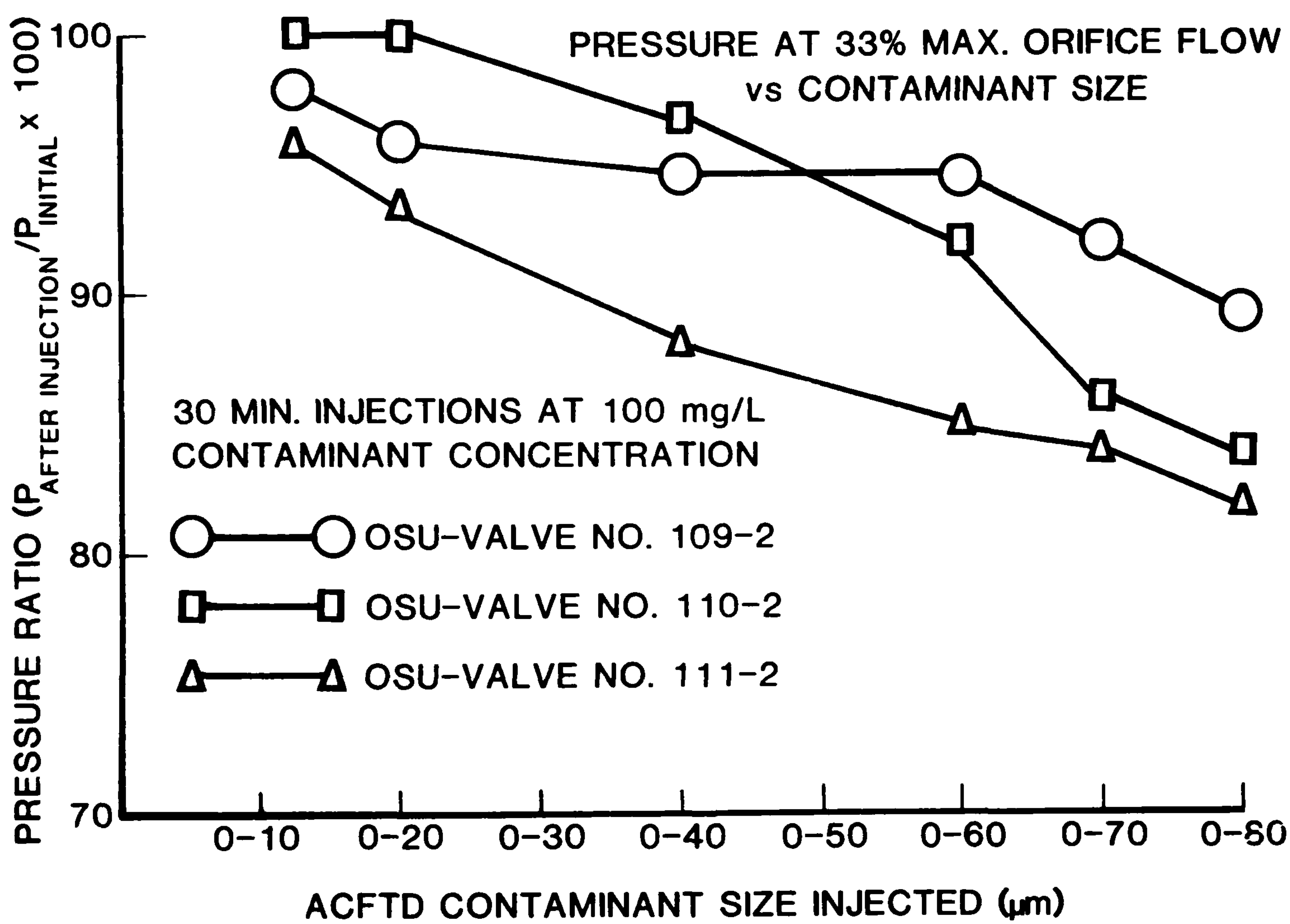


Fig 5 Linear Plot of Pressure Degradation Versus Contaminant Size Injected



Pressure Degradation of Relief Valves Due to Contaminant.

Fig. 5-5 Pressure Degradation of Relief Valves Due to Contaminant

sensitivity. The following chapters deal with the relief valve degradation theory and the computer program which was developed to utilize this important concept.

CHAPTER VI

DEVELOPMENT OF A DATA INTERPRETATION TECHNIQUE

Although much can be learned from a simple examination of experimental test data, a complete understanding of the process which occurs during a contaminant sensitivity test is impossible without some theoretical insight concerning the matter. This insight can be gained by basing all thought and consideration of the process on a theory which logically explains the mechanism by which the phenomenon occurs. Thus as stated in earlier chapters, a relief valve contaminant sensitivity theory should be developed in order to adequately fulfil the goals set forth in this research study. The following paragraphs present the relief valve contaminant sensitivity theory which was developed at the FPRC. The applications of this theory to contaminant sensitivity test data will be discussed.

To verify the title of the preceeding theory, contaminant sensitivity refers to the performance degradation which a hydraulic component will exhibit when exposed to specific contamination levels of the fluid. The characteristic contaminant sensitivity of a component has been proven to be dependent upon the range of contaminant particle sizes and their concentration in the fluid.

The rate at which the performance of a component degrades is dependent upon the contaminant sensitivity (S_i) of the component for each range, i, and the rate at which these same size particles are exposed to the component. Thus, for a concentration of n particles per

milliliter in the size range i, a component with a contaminant sensitivity of S_i for the above conditions being exposed to $N_i(t)$ particles, the rate at which the component's performance (p) will degrade is expressed by the following accepted contaminant wear equation:

$$\frac{dp}{dt} = -S_i(n)\frac{dN_i(t)}{dt} \tag{6-1}$$

For all components, the rate at which particles of any size range are exposed to their internal parts at any time t, for a flow rate of Q and a particle concentration of n is given by:

$$\frac{dN_i(t)}{dt} = Q(t)n(t) \tag{6-2}$$

The laboratory conditions where particles are injected into the fluid and left to circulate until the end of that particular test period is unlike that which occurs in the field. In the actual case, particles are constantly being impressed into the system fluid while at the same time other particles are being filtered out. This condition results in essentially a stabilized contamination distribution in the fluid. Because contaminant particles are destroyed in the passages and clearances of both laboratory and field system pumps, there is a difference in the degradation characteristics which will occur in each. This difference should be accounted for when considering laboratory degradation data. The rate at which particles are destroyed in the passages of fluid power pumps can be expressed as:

$$n(t) = n_0 e^{-t/\tau}$$

where n_o is the initial concentration of particles in the fluid. The quantity τ represents the exponential time constant for the particle destruction process for the particle size range under consideration. The above expression therefore determines the number of particles per unit volume in the size range of interest which will still contribute to the degradation at any time after the initial injected or ingression of particles. This topic concerning the destruction time constants and their effects will be discussed in detail in Chapter VII of this report.

It has been verified that the contaminant sensitivity of a component is a linear function of the concentration, n. Thus, the sensitivity, s, can be defined as:

$$s(n) = \alpha n(t) \tag{6-4}$$

where α ia a constant referred to as the contaminant wear coefficient with units of $(\text{volume/particles})^2$ per unit time.

For the case of relief valves, performance is taken to be the system pressure, P, which results from an induced relief flow, Q through the valve. Thus substituting Eq. (6-2), (6-3), and (6-4) into Eq. (6-1) yields the differential equation:

$$\frac{dP}{dt} = -\alpha n_o^2 Q e^{-2t/\tau} \tag{6-5}$$

Eq. (6-5) defines the rate of pressure degradation of a relief valve with respect to the component's contaminant wear coefficient,

particle concentration, relief flow, and the particle destruction time constant at time t.

For the smaller size contaminant injections (0-5μm, 0-10μm), degradation was observed to occur as a linear function of time, Fig. [6-1]. This can be explained by the assumption that for these smaller sizes, the time constants for the destruction process is very large. This has the effect of essentially maintaining a constant number of particles in that specific size range for the duration of the test. Thus, solving Eq. [6-1] for the situation of a constant particle number result in;

$$P(t) = P_0 - \alpha n^2 Q t \qquad (6\text{-}7)$$

which is the same type relationship as is illustrated in Fig. [6-1].

An important note is that in actual field operation, the pressure would degrade in the fashion described by Eq. (6-7) for all particle sizes.

With the degradation equations (6-6) and (6-7) along with experimental degradation data, the values of the contaminant wear coefficients can be derived for all size ranges of contaminant. This value can in turn be used to compute the life of the component which can be expected in the field, given any operating condition.

The interfacing of the relief valve contaminant sensitivity theory with a customized computer program to do the required calculations will be presented in Chapter VIII.

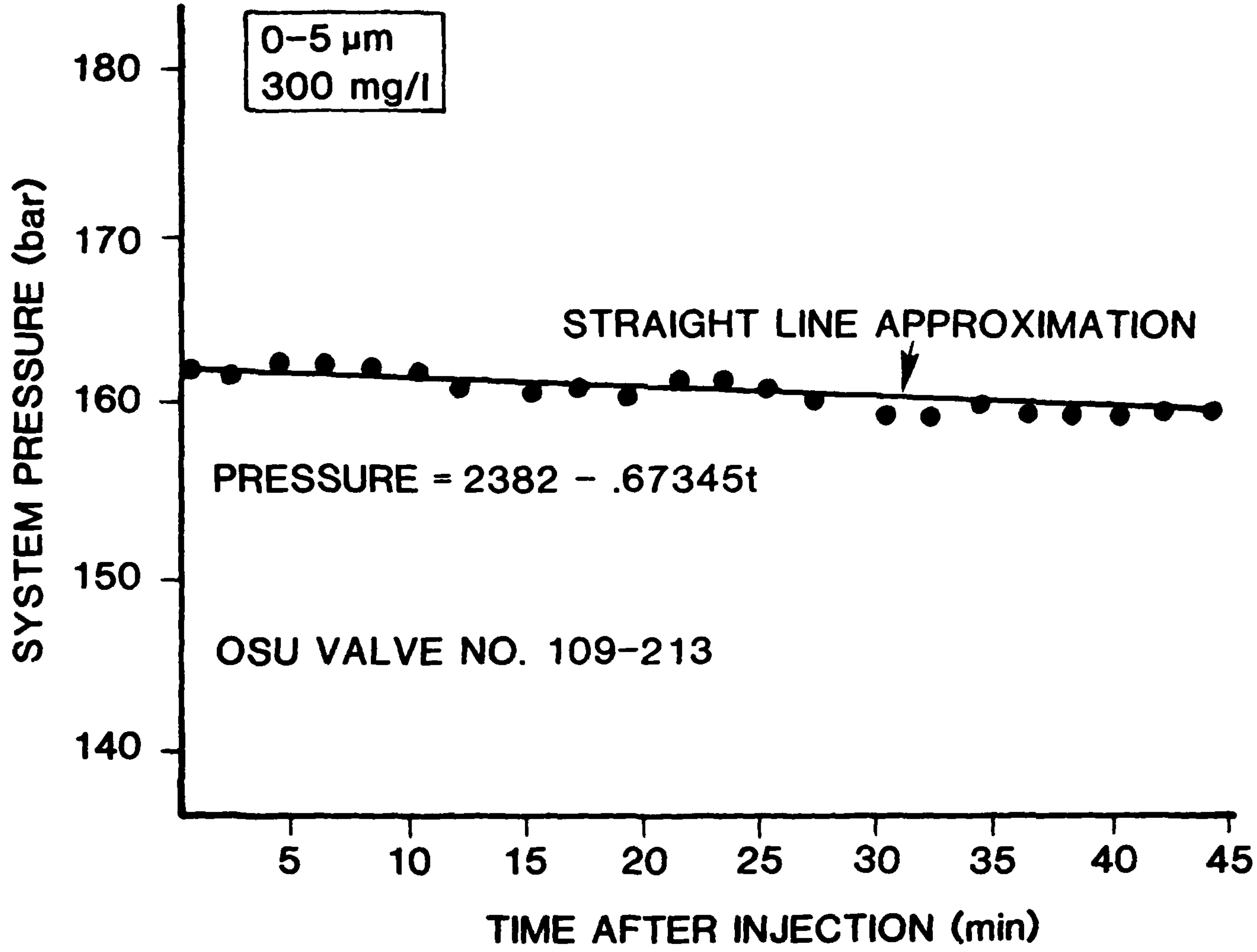


Fig. 6-1 Relief Valve Pressure Due to Very Small Contaminants

Summarizing, this chapter has presented in final form the set of equations which form the theoretical basis for the majority of the considerations followed throughout this research effort. Because the theory presented represents both laboratory and field performance degradation characteristics, the conversion from laboratory degradation data to applicable field life information is easily obtainable. Finally, the confidence in the relief valve contaminant sensitivity theory which is a requisite for all standardized evaluation techniques is strengthened by the fact that this approach is based on the identical set of equations which formulate the world renowned pump contaminant sensitivity theory.

CHAPTER VII

LABORATORY CONTAMINANT DESTRUCTION PROCESS AND IT'S EFFECTS ON EXPERIMENTAL DATA

As reported in Chapter VI, the rate at which the performance of a fluid power relief valve is degraded is largely dependent upon the behavior of the contaminants in the fluid. In particular, the test life of laboratory contaminants has a significant influence on the characteristic degradation exhibited by components in the laboratory. In order to better relate laboratory degradation information with actual field degradation, a study to determine the effects of contaminant destruction during testing was undertaken.

Contaminant particles are known to be destroyed or altered due to the harsh conditions to which they are exposed inside the pump of a system. In the past, this destruction has been thought to be related with the wear phenomenon which occurs in hydraulic pumps (Ref. [2]). This concept understood the destruction rate of a particular size range of contaminant particles to be directly observable by the wear rates which this size range caused in the pump. For large particles which cause substantial amounts of wear, the destruction rates are very high. Likewise, for small particles which generally contribute little to the degradation of a pump, the destruction rates are low. As with the relief valve contaminant sensitivity theory, the pump contaminant sensitivity theory utilizes a quantity referred to as the particle destruction time constant, τ. This quantity is simply the

time it takes for a group of particles of size to be reduced to 37% of their original number of particles. This therefore assumes that the destruction process is exponential in nature. The equation which has been taken to describe the particle destruction process is:

$$n(t) = n_0 e^{-t/\tau} \qquad (7\text{-}1)$$

for each particle size range. In this expression, $n(t)$, is the particle number per unit volume at any time t, n_0 is the original number of particles per unit volume, and τ is the particle destruction time constant. Although it has been conceded that this expression is likely to be inaccurate when strictly considering particle size destruction, it seems to be essentially correct when the overall process of particle alteration is considered. Because the entire background upon which this assumption is based relies upon data generated during actual pump contaminant sensitivity testing, the effect of wear material becoming intermixed with the laboratory contaminant was unavoidable. Therefore, due to the impact which particle destruction has on test results, a new effort was conducted to determine the behavior of contaminant particles in a laboratory test circuit. This study intended to examine fluid samples taken from a system containing a verified contaminant insensitive pump. In this way, wear material would have no influence on particle counts conducted on the samples. Also, closer related to relief valves, the effect on particle destruction which a relief valve in the system contributes was examined.

For the series of tests, a circuit similar to that used for relief valve testing was used (Fig. (7-1)). After filtering the fluid to obtain a contaminant concentration level of less than 10mg/ℓ, classified AC Fine Test Dust (0-80μm) was injected into the system to bring the contaminant concentration level to 100 mg/ℓ. Injection was carried out over a period of time numerically equal to one complete circulation of the system volume. System flowrate was adjusted such that the entire volume of the system would circulate two times per minute as in the relief valve test procedure. The pressure at which the system was operated was maintained constant at 3000 psi at a fluid temperature of 150°F using MIL-L-2104 as the working fluid. Fluid samples were extracted at 40 seconds, 2 minutes, 4 minutes, 8 minutes, and 16 minutes after completion of the contaminant injection. A particle size distribution analysis was conducted on each of the samples using a multi-channel liquid automatic particle counter HIAC Model PC-320 calibrated in accordance with the standard AC Fine Test Dust procedure, ISO 4402.

A plot of the current interval size particle number divided by their respective particle number at 40 seconds versus time after injection illustrates the particle reduction process which occurs, Fig. (7-2). It can be seen that for the particles in the size ranges greater than 30 micrometers, the destruction process tends to follow an exponential relationship. It can also be seen from the figure that certain small sizes of contaminant particles apparently never decrease in number. These sizes increase in number exponentially over the

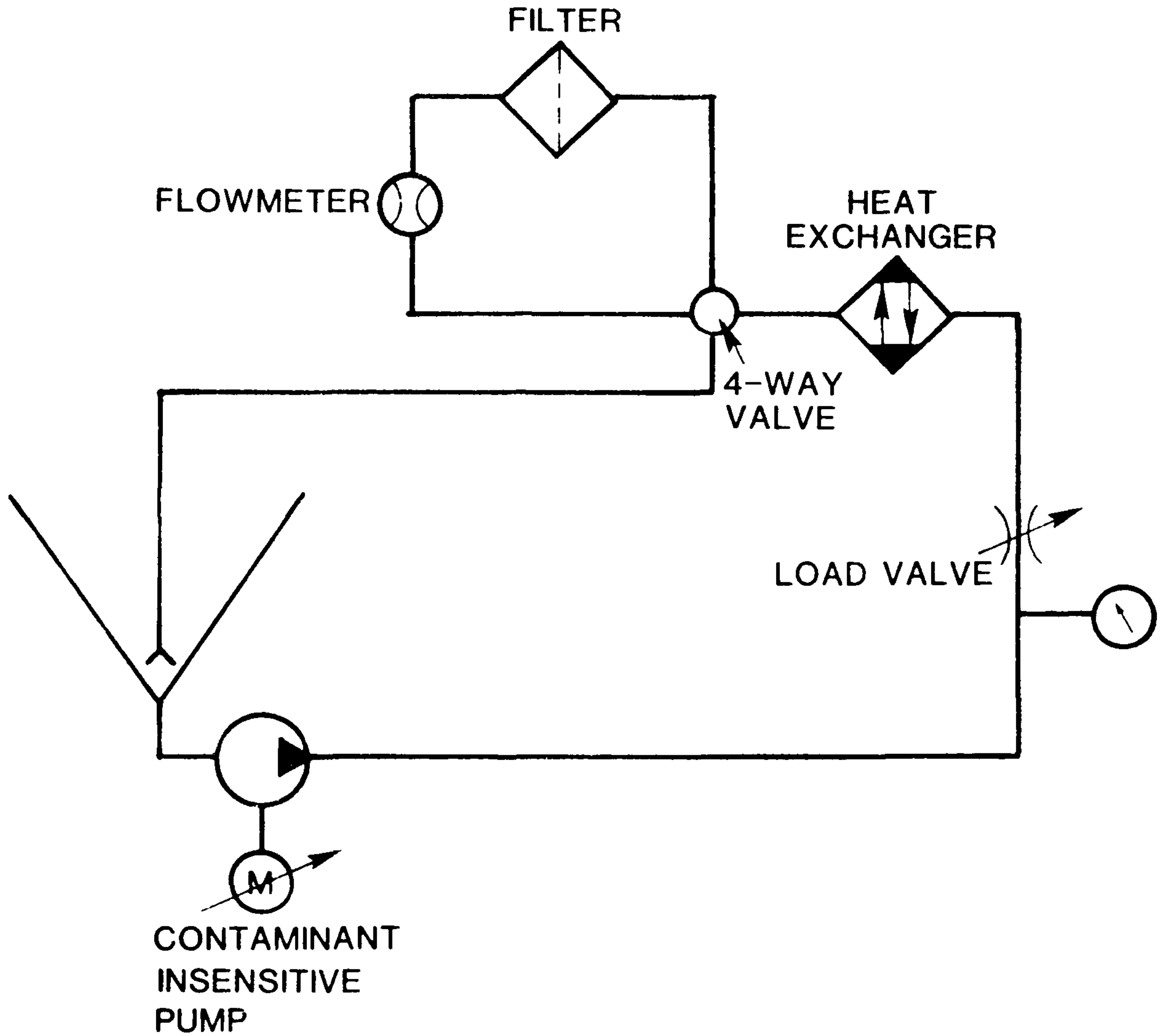


Fig. 7-1 Particle Destruction Analysis Test Circuit

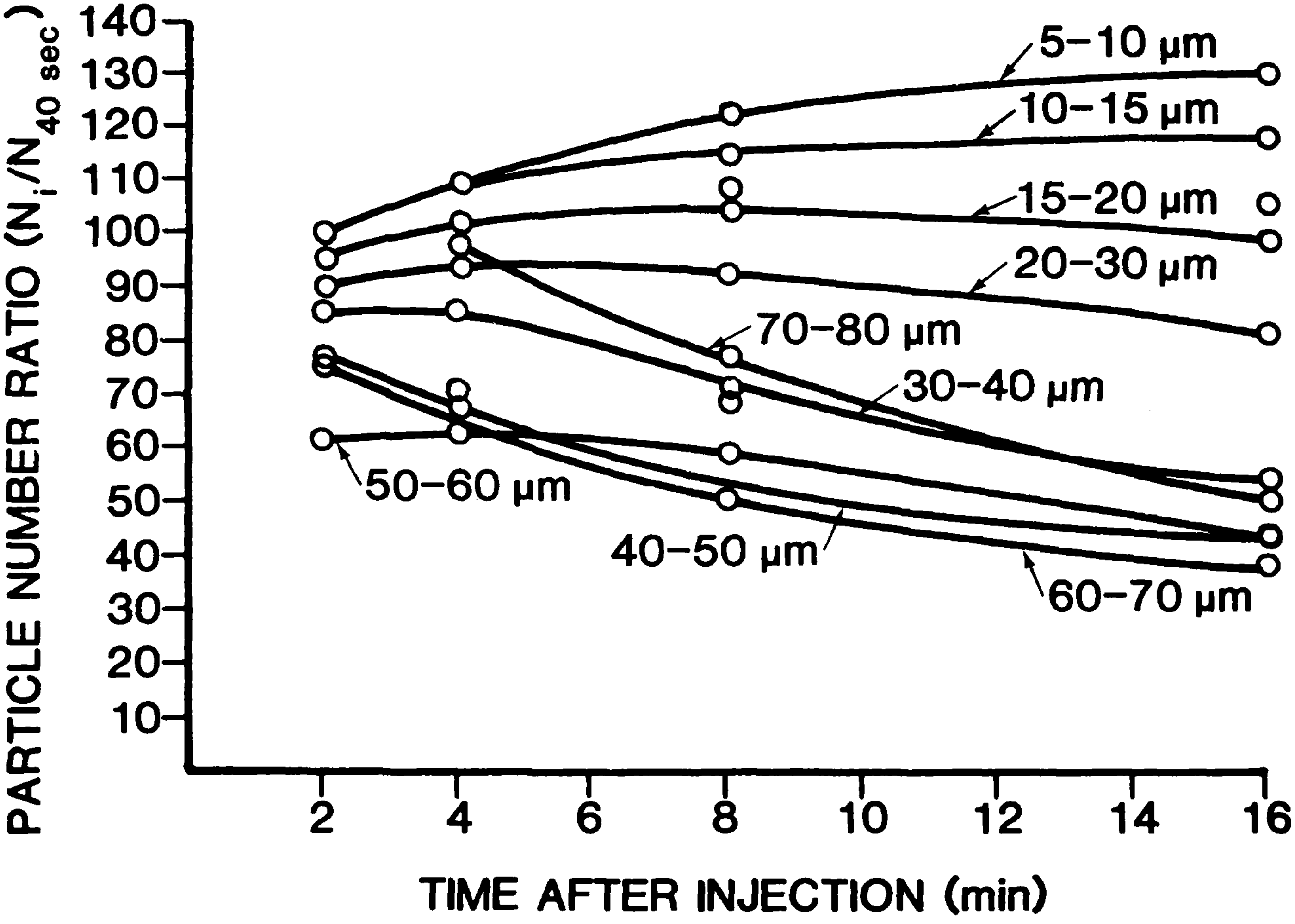


Fig. 7-2 Illustration of Particles

observation time of 16 minutes. This increase is due to larger particles "breaking-up" into smaller particles thus replenishing those small particles which are destroyed. It is recognized that if the observation period were extended, the small sizes of particles would eventually decrease in number. The important thing to remember here is that for a period of 15 minutes (the same as the amount of time which the relief valve test allows for a contaminant injection) after an injection of contaminant, small particles are not destroyed to any appreciable amount; however, for large particles, the destruction process does occur.

For those particles which are decreasing in number, the relationship appears to be exponential in nature; therefore, a mathematical model to describe the process can be derived. Using a least squares fit exponential to best describe the particle number decrease, values for the time constant, τ, in Eq. (7-1) were calculated along with their correlation coefficients. The correlation coefficients are a measure of how closey the model approximates the acutal test data--a value of +1 representing a perfect correlation, values approaching 0 indicating a poor correlation. Table (7-3) lists the time constants and correlation coefficients for those particle size ranges which exhibited decreasing numbers within the 16 minute observation period. Again, this information was derived using a verified contaminant insensitive pump.

Table 7-3 List of Computed Particle Destruction Time Constants and Correlation Coefficients for OSU Test Pump No. 102

PARTICLE DESTRUCTION TIME CONSTANT FOR OSU TEST PUMP NO. 102		
PARTICLE SIZE INTERNAL (μm)	TIME CONSTANT τ (minutes)	CORRELATION COEFFICIENT
15–20	84	–.99
20–30	55	–.96
30–40	24	–.99
40–50	22	–.99
50–60	19	–.98
60–70	17	–.96
70–80	21	–.98

Fig. (7-4) is a plot of the particle destruction time constants versus their respective particle size. The large time constants for the smaller size ranges is due to the large particles constantly contributing to that size range as quickly as the small particles are themselves being destroyed. It has therefore been concluded that the time constant can be taken to be a linear function of the particle size. Thus, the curve of Fig. (7-4) is approximated with a straight line passing through the larger particle size end of the graph as shown in Fig. (7-5).

In order to gain more insight into the particle destruction process, the procedure described earlier was repeated using a different contaminant insensitive pump. The results of this analysis as shown in Table (7-6). Comparing this data with that for OSU TEST PUMP No. 102 presented an interesting observation. As shown in Fig. (7-7), Pump No. 102 exhibits consistently higher particle destruction rates than pump No. 101. This is partically explained by the fact that No. 101 is substantially older than No. 102. Thus sharp edges and small clearances inside the pump are less damaging due to the wear which has occured inside the pump over it's years of operation. The point to be made is that both pumps have their own individual particle destruction characteristics, viewpoint which was not taken in past considerations.

As with pump No. 102, the time constant curve was linearized to fit the large particle end of the graph. The time constants for both

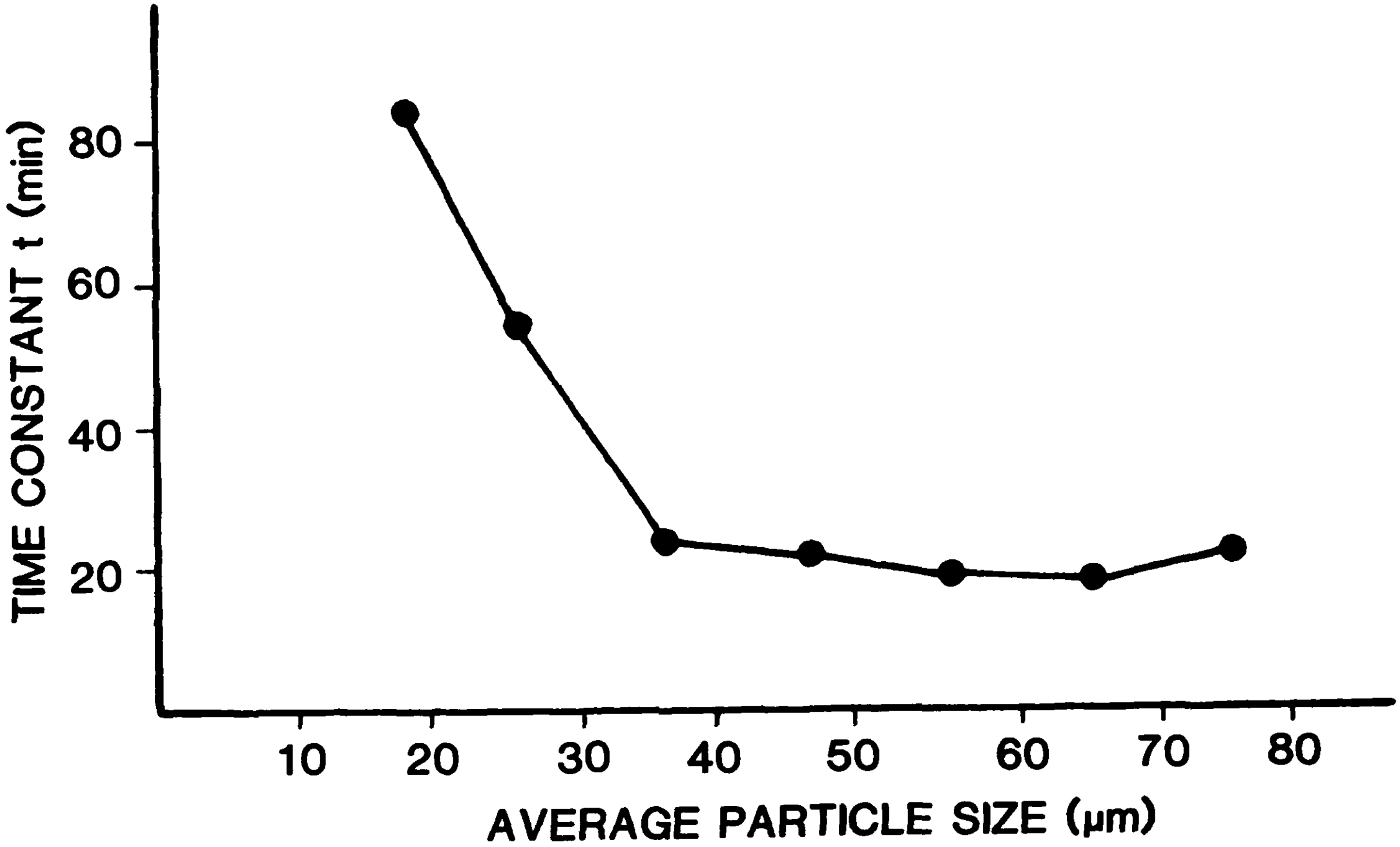


Fig. 7-4 Plot of Particle Destruction Time Constants versus Particle Size

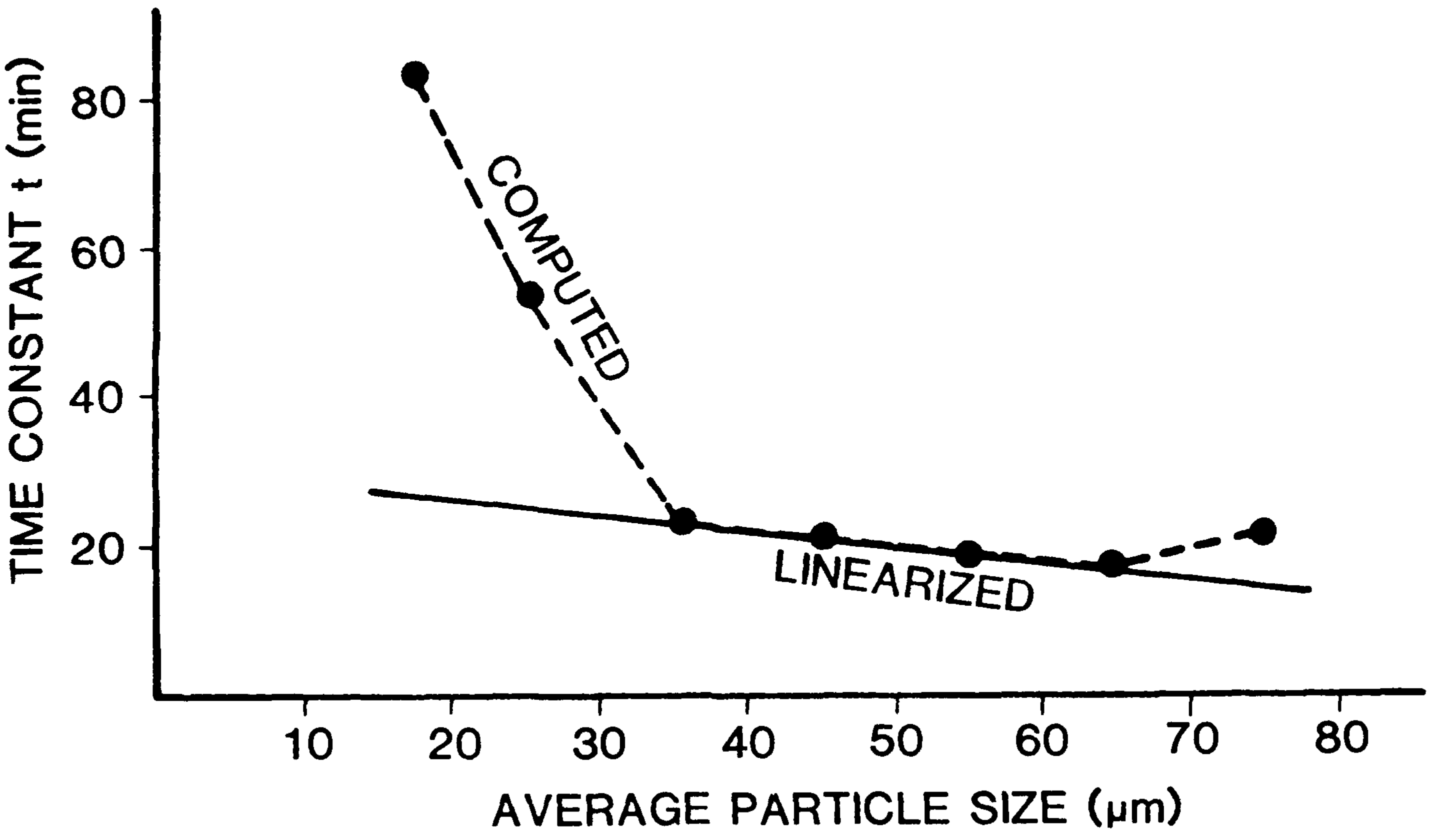


Fig. 7-5 Linearized Particle Destruction Time Constant Relationship for OSU Test Pump No. 102

Table 7-6 List of Computed Particle Destruction Time Constants and Correlation Coefficients for OSU Test Pump No. 101

PARTICLE DESTRUCTION TIME CONSTANT FOR OSU TEST PUMP NO. 101		
PARTICLE SIZE INTERNAL (μm)	TIME CONSTANT τ (minutes)	CORRELATION COEFFICIENT
18–20	69	–.989
20–30	—	—
30–40	57	–.988
40–50	41	–.983
50–60	25	–.998
60–70	20	–.935
70–80	13	–.98

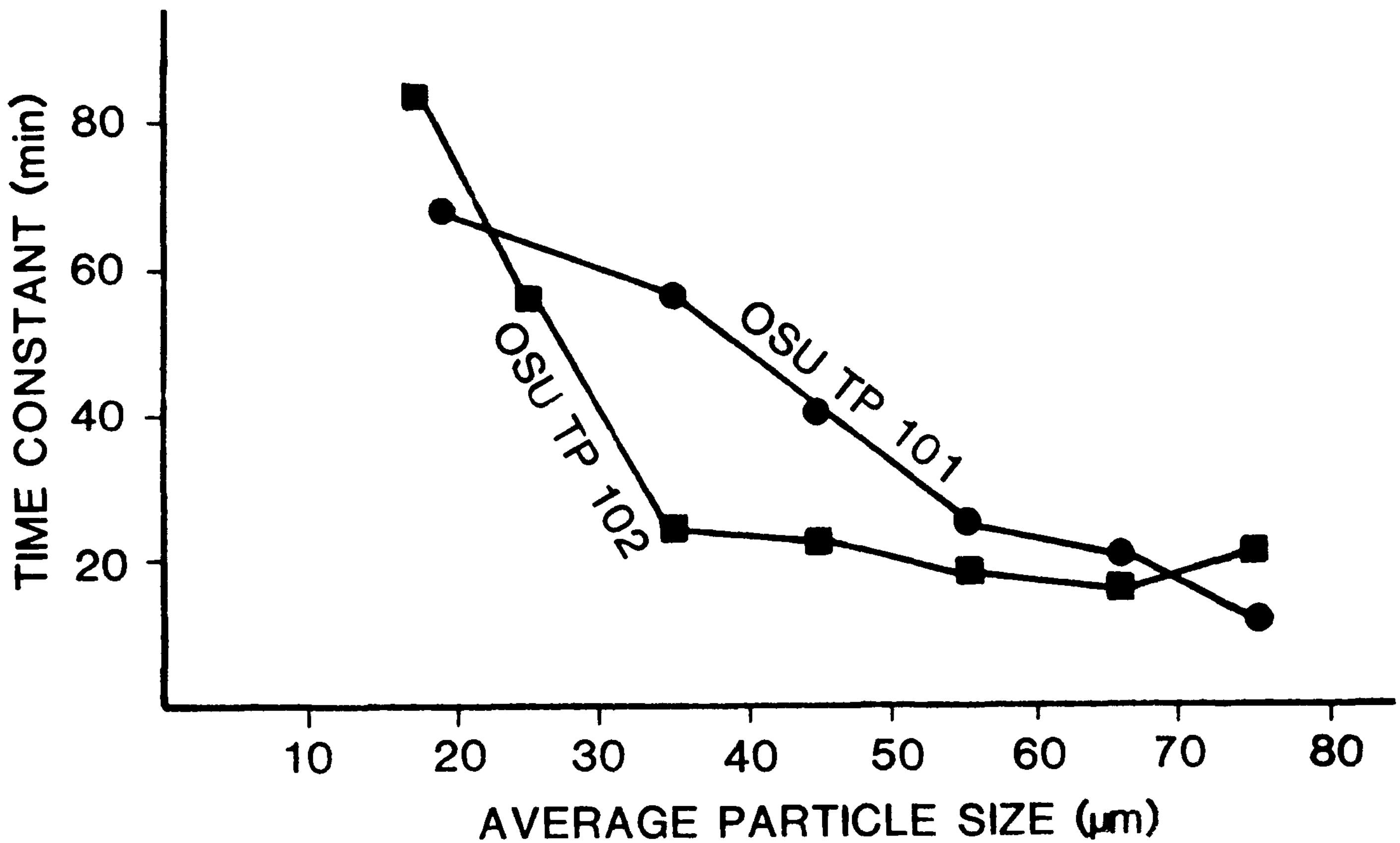


Fig. 7-7 Comparison of Particle Destruction Time Constants for OSU Test Pumps 101 and 102

pumps taken from the linearized curve are shown in Table (7-8). This information will be used in the data interpretation procedure and will be cataloged as constant values. With this information available, the performance degradation rates observed in the laboratory can be better understood.

Tests identical to that for evaluating relief valves contaminant sensitivity were conducted to determine the effect of the relief valve on the particle destruction process. Operating at the same conditions as before, particle counts were conducted on samples extracted from the fluid during testing. Results from this analysis are consistent with those from tests without the relief valve in the circuit.

Making use of the information gained from this study, the direct effects of contaminant particle destruction in the laboratory can be better understood. Referring to the basic pressure degradation equation presented in Chapter VI:

$$P(t) = P_o - \tfrac{1}{2}\alpha n_o^2 Q\tau(1 - e^{-2t/\tau}) \qquad (7\text{-}2)$$

it can now be realized the importance of knowing the value of the time constant, τ.

Varying τ will greatly change the severity of the pressure vs time degradation curve as depicted in Fig. (7-9a). Also, as in the case of small particles, this type relationship is illustrated in Fig. (7-9b).

After considering the effects which the time constants have on laboratory degradation rates, the staff at the FPRC recommend that

VALVE TEST PUMP NO.	CONTAMINANT DESTRUCTION RATE TIME CONSTANT (min)								
	0–5	5–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80
101			48	42	36	29	22	16	9
102			28	26	23	21	18	15	12

Table 7-8 Linearized Valves of the Particle Destruction Time Constants for OSU Test Pumps 101 and 102

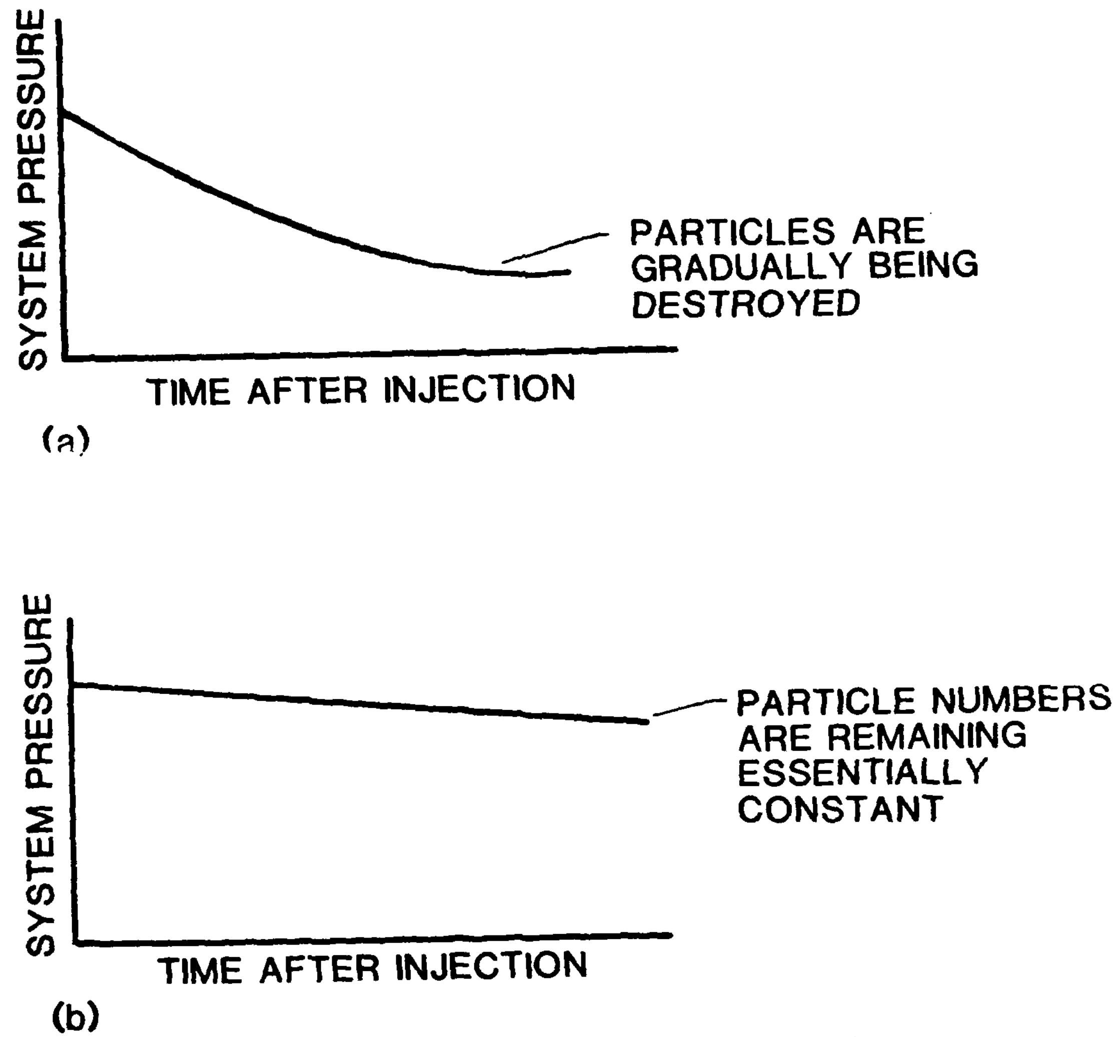


Fig. 7-9 Pressure Degradation Characteristics Due to Large (a) and Small (b) Contaminant Particles

prior to conducting the relief valve contaminant sensitivity evaluation procedure as described earlier, an analysis of the particle destruction characteristics of the test system pump which will be used should be conducted. This information is a requisite for the proper evaluation of a relief valve contaminant sensitivity.

This chapter was intended to divulge the latest work which has been done in the area of laboratory particle destruction. The basic conclusions drawn as a result of this study are:

1. Particle destruction rates are of vital importance to the degradation rate of a relief valve.
2. Particle destruction rates are a characteristics of the specific test system pump and are not necessarily constant for all particle sizes.

This new understanding of the effect of particle destruction in the laboratory on the performance degradation rate of a component will greatly enhance the reliability of the relief valve contaminant sensitivity data interpretation technique and hopefully given better insight into the other aspects of contaminant sensitivity testing.

CHAPTER VIII

RELIEF VALVE OMEGA RATING SYSTEM

Application of Data Interpretation Technique

The pressure degradation of relief valves due to contaminant is expressed by the following equation from Chapter VI, assuming a constant particle number such as that encountered in the field.

$$P(t) = -\alpha n^2 Qt + P_o \qquad (8\text{-}1)$$

where: $P(t)$ = pressure at time t

α = contaminant wear coefficient

n = particle number per unit volume

Q = flow rate

t = test time

P_o = initial pressure.

Experiments have verified that for the test contaminant sizes 0-5μ and 0-10μm, the particle destruction process has a negligible effect on the particle numbers in these size ranges. Thus, the assumption of constant particle number of these sizes is acceptable. For this reason, (8-1) represents the pressure degradation relationship which is valid for particle sizes up to 10μm. The experiments also verified that for contaminant sizes larger than 10μm, particle destruction must be acknowledged. (Detailed discussion on particle destruction was presented in Chapter VII.) Pressure degradation under the condition of particles being destroyed can be expressed by Eq. (2):

$$P(t) = P_o + 1/2\alpha Q n_o^2 \tau (e^{-2t/\tau} - 1) \qquad (8\text{-}2)$$

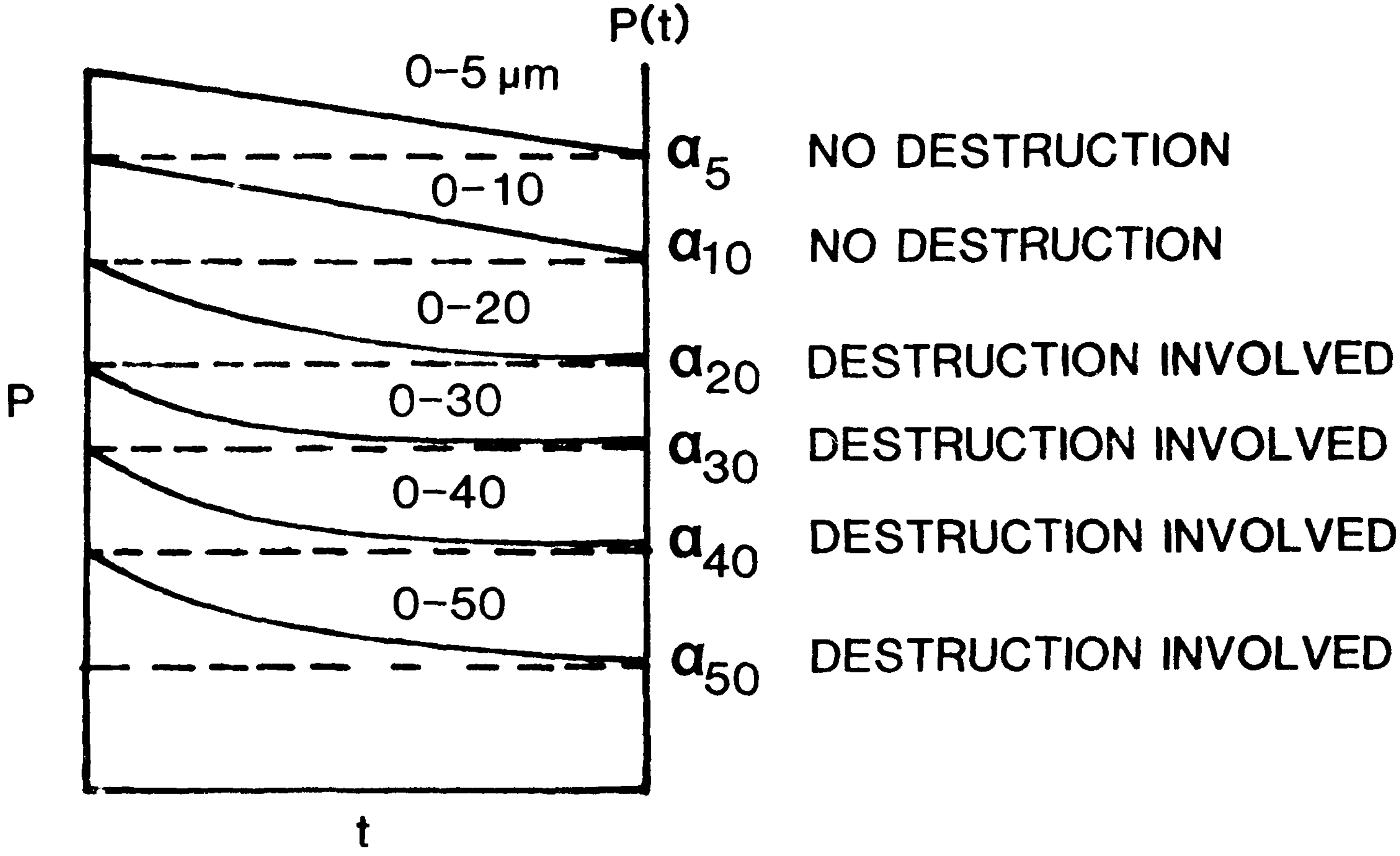


Fig. 8-1 Schematic of Pressure Degradation due to Various Size Particles

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where: τ = particle destruction time constant.

The pressure degradation due to different contaminant sizes in the laboratory test is illustrated in Fig. (8-1).

Since Eq. (8-1) holds for the contaminant sizes of 0-5μm and 0-10μm, the contaminant wear coefficient α for 0-5μm is expressed by Eq. (8-3) which is a modification of Eq. (8-1).

$$\alpha_{0-5} = \frac{P_o - P_{f0-5}}{n^2 Qt} \tag{8-3}$$

where: α_{0-5} = contaminant wear coefficient for 0-5μm

P_o = initial pressure

P_{f0-5} = final pressure with 0-5μm contaminant during the test time t.

The pressure degradation due to 0-10μm contaminants is the combined effect of 0-5μm contaminants. This situation can be expressed mathematically as in Eq. (8-4).

$$\Delta P_{0-10} = \Delta P_{\frac{0-5}{0-10}} + \Delta P_{\frac{5-10}{0-10}} \tag{8-4}$$

where: ΔP_{0-10} = pressure degradation due to 0-10μm contaminant

$\Delta P_{\frac{0-5}{0-10}}$ = pressure degradation due to 0-5μm contaminant included in 0-10μm contaminant injection

$\Delta P_{\frac{5-10}{0-10}}$ = pressure degradation due to 5-10μm contaminant included in 0-10μm contaminant injection.

Eq. (8-4) can be rewritten as:

$$P_{f0-10} - P_o = P_{f\frac{0-5}{0-10}} - P_o + P_{f\frac{5-10}{0-10}} - P_o \tag{8-5}$$

Further manipulation yeilds:

$$P_{f0-10} = -\alpha_{0-5} n^2_{\frac{0-5}{0-10}} Qt + P_o - \alpha_{5-10} n^2_{\frac{5-10}{0-10}} Qt \tag{8-6}$$

where: α_{5-10} = contaminant wear coefficient for 5-10μm contaminant

$n_{\frac{0-5}{0-10}}$ = particle number per unit volume of 0-5μm contaminant included in 0-10μm contaminant injection

$n_{\frac{5-10}{0-10}}$ = particle number per unit of volume of 5-10μm contaminant included in 0-10μm contaminant injection.

From Eq. (8-6), α_{5-10} can be calculated by Eq. (8-7).

$$P_{f0-20} = -\alpha_{0-5} n^2_{\frac{0-5}{0-20}} Qt + P_o - \alpha_{5-10} n^2_{\frac{5-10}{0-20}} Qt + 1/2\,\alpha_{10-20} Q n^2_{\frac{10-20}{0-20}} \tau_{10-20} (e^{-2t/\tau_{10-20}} - 1) \tag{8-7}$$

Derivation of the contaminant wear coefficients for all interval size contaminants is summarized in the following.

$$\alpha_1 = (P_o - P_{f1})/(n^2_1 Qt) \tag{8-8}$$

$$\alpha_2 = \frac{1}{n^2_{2/2}} \left(\frac{P_o - P_{f2}}{Qt} - \alpha_1 n^2_{1/2}\right) \tag{8-9}$$

$$\begin{aligned}\alpha_3 = {} & 2(P_{f3} - P_o + Qt(\alpha_1 n^2_{1/3} + \alpha_2 n^2_{2/3})) \\ & /(Q n^2_{3/3} \tau_3 \times (e^{-2t/\tau_3} - 1))\end{aligned} \tag{8-10}$$

$$\begin{aligned}\alpha_i = {} & 2(P_{fr} - P_o + Qt(\alpha_1 n^2_{1/r} + \alpha_2 n^2_{2/r}) \\ & - 1/2Q \times \sum_{j=3}^{i-1} \alpha_j n^2_{j/r} \tau_j (e^{-2t/\tau_j} - 1)) \\ & /(Q n^2_{i/r} \tau_i (e^{-2t/\tau_i} - 1)), \quad i = 4, 5, 6, \ldots i_{max}\end{aligned} \tag{8-11}$$

Where the subscript r designates a particle size range (0-5, 0-10, 0-20, etc.) and the dummy subscript (j) is used to signify a size interval (5-10, 10-20, etc.). For example:

$\alpha_1 = \alpha_{0-5}$	$P_{f1} = P_{f0-5}$	$n_1 = n_{0-5}$	$\tau_3 = \tau_{10-20}$
$\alpha_2 = \alpha_{5-10}$	$P_{f2} = P_{f0-10}$	$n_{1/2} = n_{\frac{0-5}{0-10}}$	$\tau_4 = \tau_{20-30}$
$\alpha_3 = \alpha_{10-20}$	$P_{f3} = P_{f0-20}$	$n_{2/2} = n_{\frac{5-10}{0-10}}$	$\tau_5 = \tau_{30-40}$
$\alpha_4 = \alpha_{20-30}$	$P_{f4} = P_{f0-30}$		$\tau_6 = \tau_{40-50}$
.		$n_{1/3} = n_{\frac{0-5}{0-20}}$	$\tau_7 = \tau_{50-60}$
.		$n_{2/3} = n_{\frac{5-10}{0-20}}$	$\tau_8 = \tau_{60-70}$
.			$\tau_9 = \tau_{70-80}$
$\alpha_9 = \alpha_{70-80}$			

The alpha values which are derived using laboratory test data represent the characteristic susceptibility to contaminant wear for a particular relief valve. Expounding further, the alpha value is strictly an "intrinsic" property of a component and is independent of the operating conditions of the valve.

Thus, using these values, the service life of a component can be predicted given any specified operating condition. The general equation for the service life of a component given a particular contaminant distribution is expressed Eq. (8-12).

$$T = \frac{P_o - P_f}{Q} \Big/ \sum_{i=1}^{i_{max}} \alpha_i n^2{}_i \qquad (8\text{-}12)$$

where: T = contaminant service life

P_o = initial pressure

P_f = final pressure at which the relief valve service life is considered to be over (usually 80% of P_o).

Contaminant Tolerance Profile for Relief Valves

The contaminant service life of a test relief valve in a given contaminant environment can be calculated by Eq. (8-12). By using Eq. (8-12), a "contaminant distribution" which will maintain a specified contaminant service life for the test relief valve can be determined. Since there are many different contaminant distributions possible in the field, the contaminant level which maintains a specified contaminant service life should be determined for several different distributions. A contaminant tolerance profile is defined as the locus of tangency points associated with contaminant particle distribution lines which maintains the same contaminant service life. Fig. (8-2) illustrates the derivation of a contaminant tolerance profile. Fig. (8-3) shows the 1000 hour and 10,000 hour contaminant tolerance profiles of relief valve OSU-VALVE-NO. 115. These contaminant tolerance profiles were actually calculated by the computer program which is detailed in Chapter X.

Omega Rating for Relief Valves

The relief valve Omega rating value is defined as the value of the Beta ten filter which can maintain the 1000 hour life of a given relief valve in the system with a flow rate of 75 gpm and an ingression rate of 10^8 particles per minute greater than 10μm.

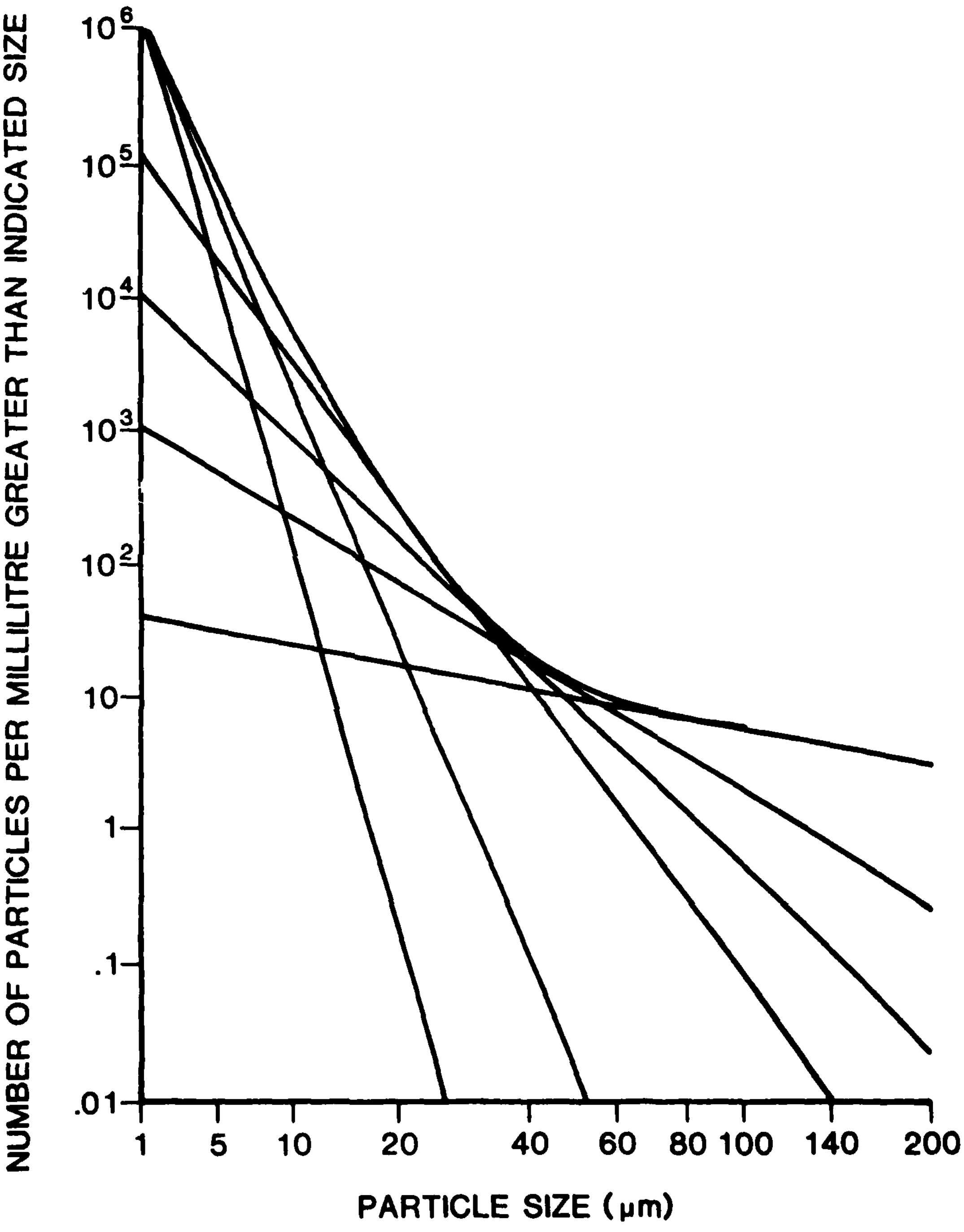

Fig. 8-2 Derivation of Contaminant Tolerance Profile

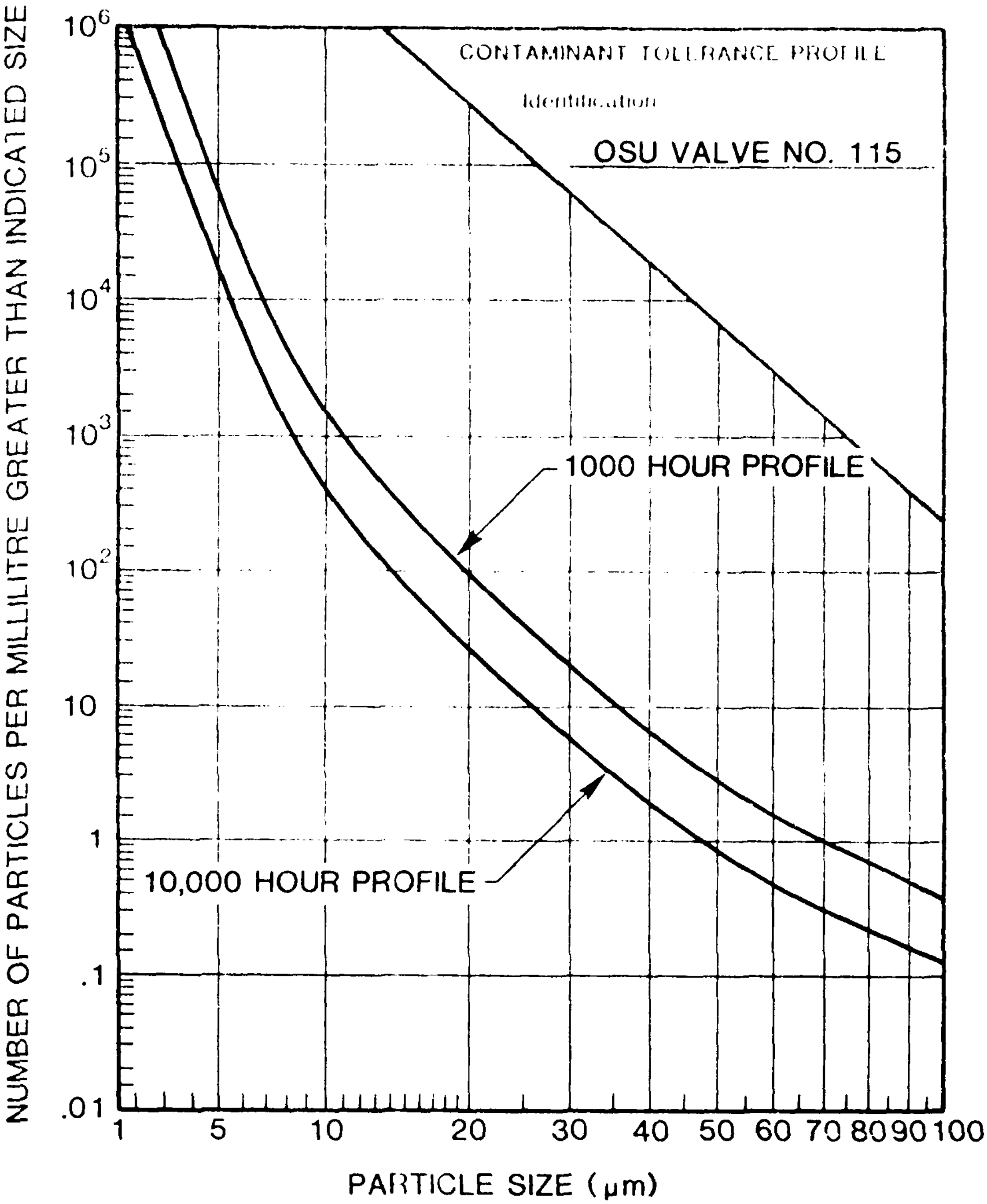

Fig. 8-3 1000 Hour and 10,000 Hour Contaminant Tolerance Profiles for OSU Valve No. 115

Fig. (8-4) illustrates the derivation of the Omega rating for relief valve OSU-VALVE-NO. 119-1. This was determined to be 15 from this chart. This Omega rating derivation was computerized and its detail is also presented in Chapter X.

The Omega rating forms a good basis for selecting the most appropriate relief valve to install in a given system. It can also predict the necessary filter protection requirement for a given relief valve in order to maintain a specified service life.

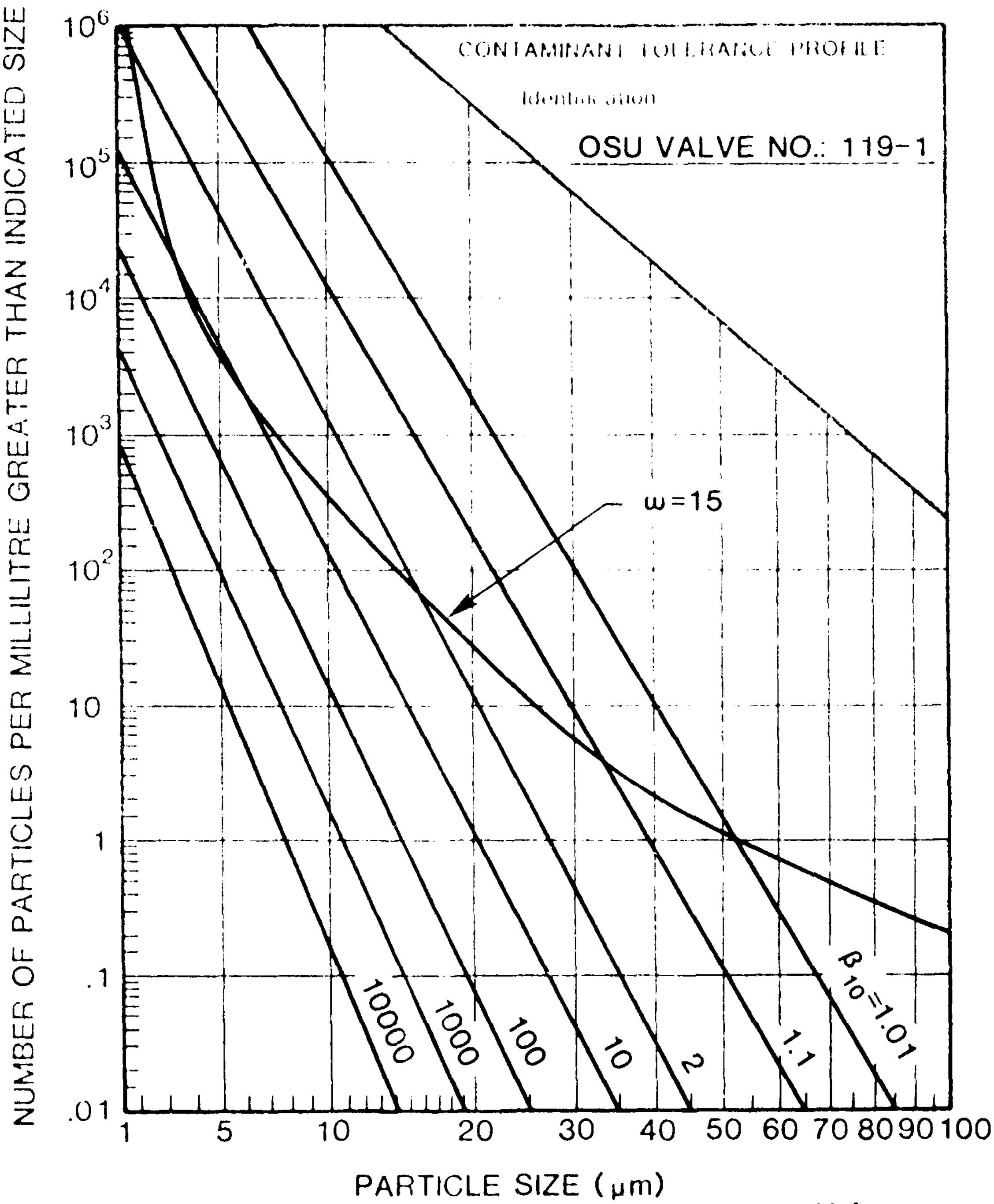

Fig. 8-4 Derivation of Omega Rating for OSU Valve No. 119-1

CHAPTER IX

PREDICTING FIELD LIFE FROM LABORATORY TEST DATA

Although the Omega rating system discussed in Chapter VIII is a very important contaminant sensitivity rating index for fluid power components, it should be realized that this value is based upon laboratory test data. If this data is generated from a test which operates the component in question at a condition unlike it will encounter in the field, the Omega value will not be exact in its specification. For example, if the test component is subjected to harsher conditions in the laboratory than it will experience in the field, the Omega value which is given to the component will be a conservative value. Although this estimate is a valuable quantity, in some instances, a more precise evaluation based on actual operating conditions is desirable.

In the case of relief valves, the above discussion is of particular interest. Because this type of valve is so versatile, a standard test procedure which could examine the entire spectrum of relief valves and their individual applications would be virtually impossible. For this reason, the relief valve contaminant sensitivity test procedure was designed to subject the test valve to the most severe conditions (maximum pressure at maximum relief flow) which it will encounter in the field. As would be expected, the life prediction which is derived will be a conservative estimate. In order to more precisely predict actual field service life, two options are available:

1. Field contaminant distribution consideration

2. Field duty cycle consideration

Using Eq. (8-12) in Chapter VIII, an initial field life prediction can be made. By utilizing the field pressure degradation equation;

$$P(t) = P_0 - \alpha n^2 Q t \tag{9-1}$$

the effect of duty cycle on field life can be considered. Both approaches will be discussed individually below.

Field Contaminant Distribution

The equation for service life is a very valuable tool for predicting the useful life which can be expected from a relief valve. Given an actual field contaminant distribution, Fig. (9-1), the contaminant wear coefficients (α), and the prescribed allowable pressure degradation, the useful service life of the valve can be predicted. This life represents the operating condition where the test valve is passing its maximum rated flow. With this value, the fluid power engineer can have valuable insight into the expected life of components which are available to use in a system.

Duty Cycle Considerations

The second option available to improve the life prediction builds on the information derived by the initial life prediction. This approach involves considering the actual field duty cycle which the valve is operated at in the field. This method requires a knowledge of the system pressure versus time relationship which is expected to occur during the

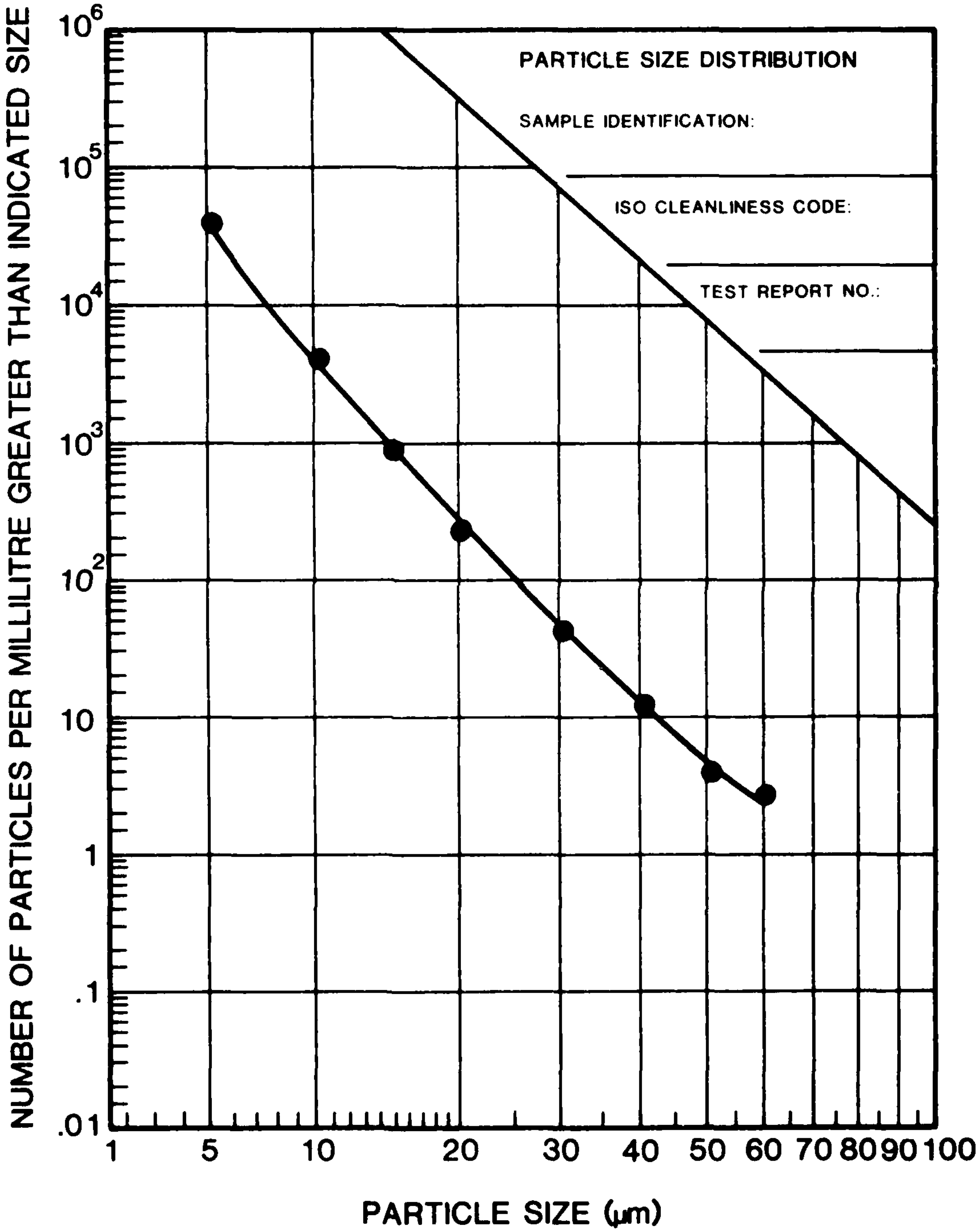

Fig. 9-1 Typical Field Contaminant Distribution

normal operation of the system which the relief valve will be a part. An example of this is shown in Fig. (9-2). This plot can be thought of as the average operating characteristics of the system. As an example, each time the bucket on a backhoe reaches its extreme position or when a sudden load is applied, the pressure in the system will increase until the system relief valve opens. Until the bucket is moved or until the load is removed, the valve will continue to pass contaminated fluid to the tank. It is during these periods of time that the majority of the wear occurs. Also, the pressure versus flow profile for the relief valve is necessary to use in conjunction with the system pressure versus time plot. From these two sets of information, two life prediction correction factors can be derived; the flow correction factor (K_F) and the exposure time correction factor (K_T). The derivation of the flow correction factor proceeds as follows:

1. From the system pressure versus time plot, determine the maximum system pressure which the relief valve will experience P_{MAX} . Fig. (9-2)
2. From the pressure versus flow profile, determine the amount of relief flow, Q_{ACT}, which accompanies P_{MAX}. Fig. (9-3).
3. Divide the relief flow, Q_{ACT}, by the maximum rated flow for the valve.

Therefore;

$$K_F = \frac{Q_{ACT}}{Q_{MAX}} \qquad (9\text{-}2)$$

To compute the exposure time correction factor, K_T, determine the

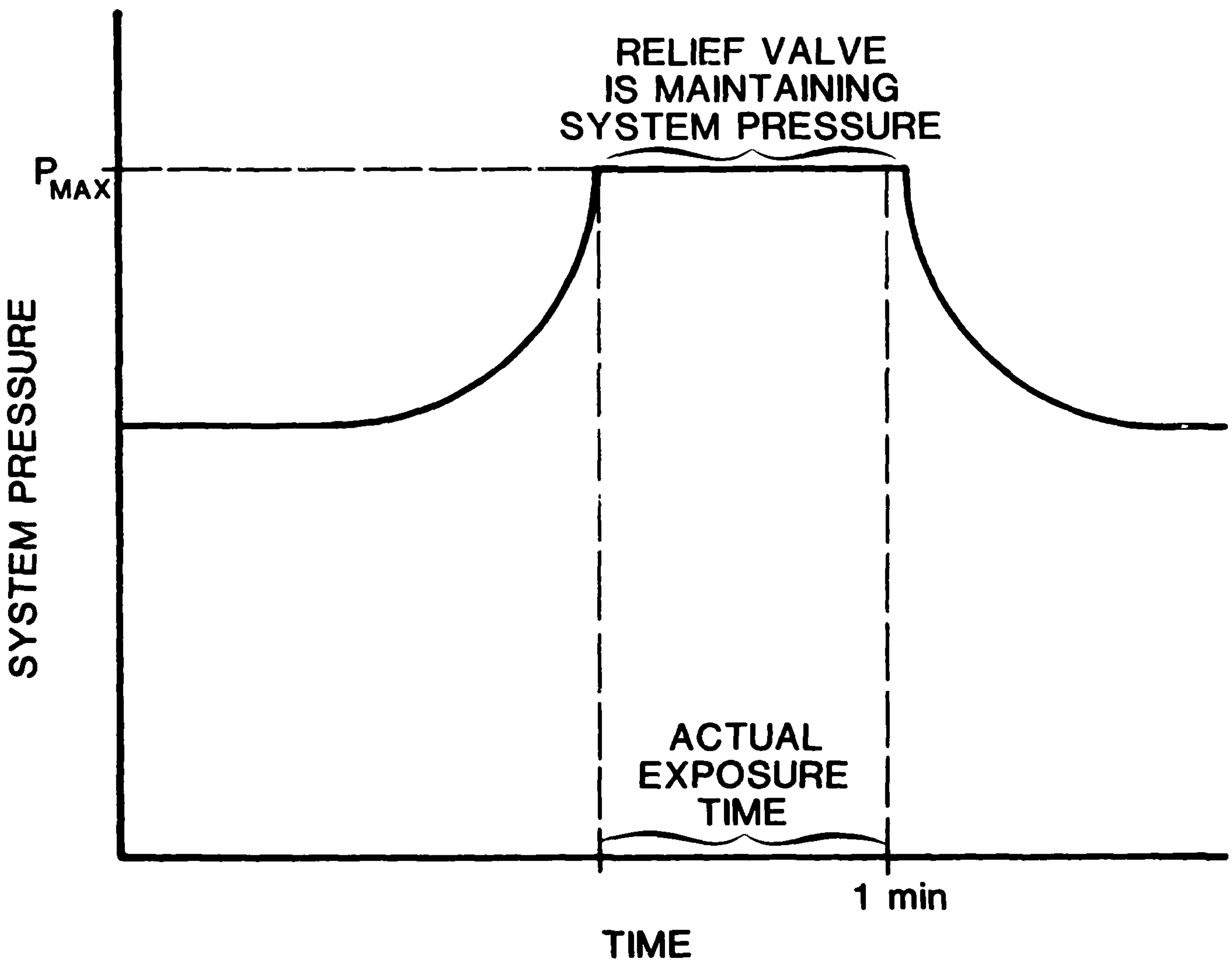

Fig. 9-2 Typical System Pressure versus Time Relationship for Hydraulic Equipment

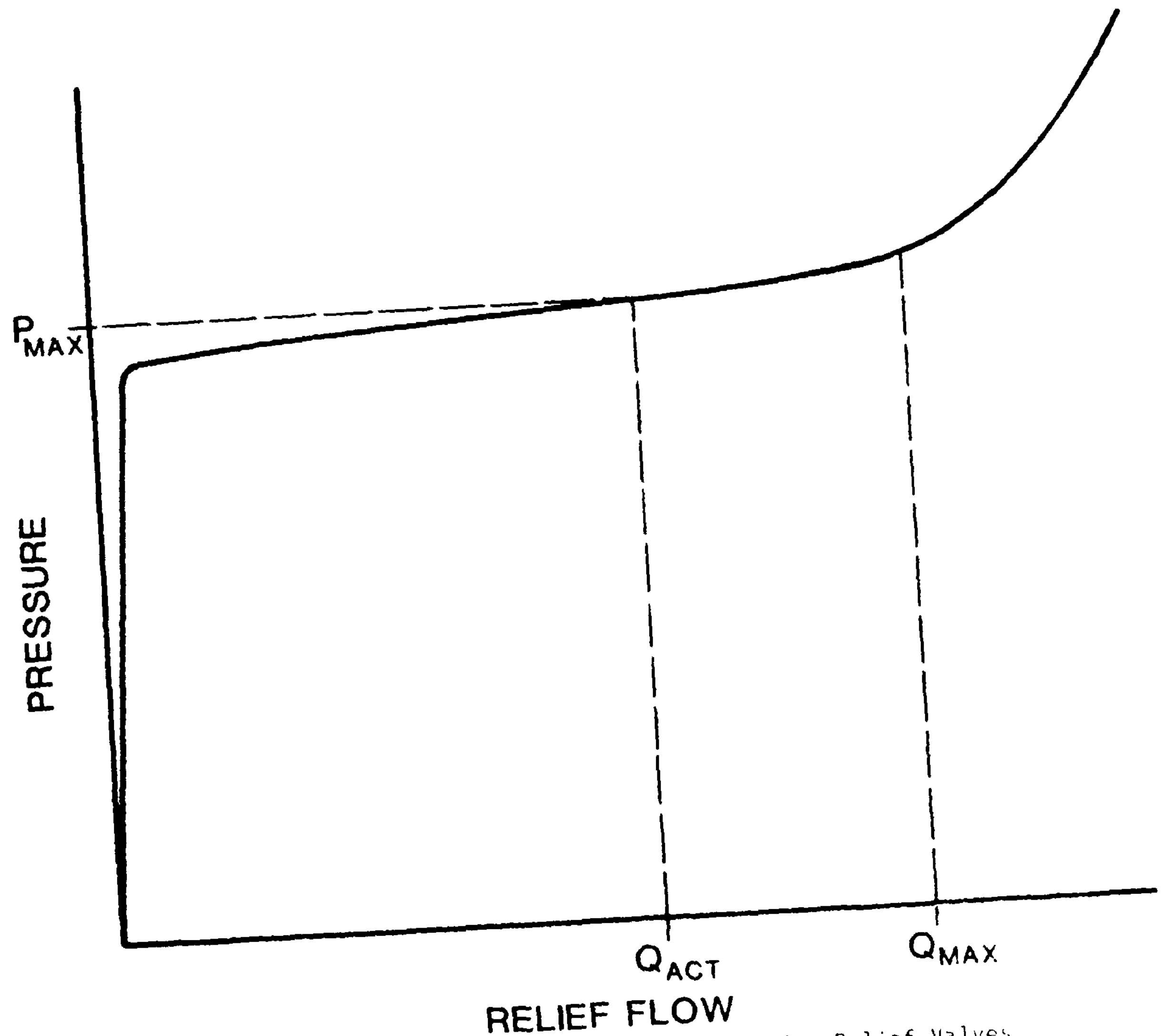

Fig. 9-3 Typical Pressure vs Flow Profile for Relief Valves

amount of time per minute during which the pressure surges are experienced (Fig. 9-2). Therefore;

$$K_T = \frac{\underline{\text{actual exposure time (sec)}}\ \text{per minute}}{60} \qquad (9\text{-}3)$$

Combining the two correction factors into a single life multiplication factor, K_L;

$$K_L = \frac{1}{K_F K_T} \qquad (9\text{-}4)$$

This value is a correction factor by which the service life, T, as calculated for the actual field contaminant distribution, is multiplied. Therefore, the service life corrected for duty cycle is determined as;

$$T_{CORR} = K_L T \qquad (9\text{-}5)$$

This simple relationship is possible when the field degradation, Eq. (9-1), is considered. As can be seen, the flow rate and exposure time are directly proportional to the amount of pressure degradation which will occur.

Although the Omega rating system is a valuable design tool, in some instances, it is desired to know or predict the life of a component given existing operating conditions. This chapter has presented two such methods by which to predict the service life of a relief valve. It should be remembered, however, that these procedures are options to the main contaminant sensitivity evaluation technique presented in Chapter

VIII and are not intended as replacements.

CHAPTER X

COMPUTER PROGRAM FOR DATA INTERPRETATION

A computer program to interpret the relief valve contaminant sensitivity test date was developed based on the data interpretation technique presented in the previous sections. The functions of the program are as illustrated in.Fig. 10-1 to:

1) Calculate the contaminant wear coefficients for interval contaminant sizes.

2) Calculate the contaminant tolerance profiles for 1000 hour and 10,000 hour expected service life.

3) Derive Omega Rating value.

4) Calculate a contaminant service life associated with a given contaminant distribution.

5) Predict a field contaminant service life associated with a given duty cycle.

The initial stage of the program consists of the contaminant wear coefficient calculation. This computes the contaminant wear coefficient (alpha) values for the interval size contaminants given test data generated in accordance with the procedures set forth in the relief valve contaminant sensitivity test introduced in Chapter V. These values represent the wear sensitivity of the valve under consideration. With the contaminant wear coefficients known, two alternatives are available to utilize this valuable information--contaminant tolerance profile calculation and field distribution life calculation. Because the first

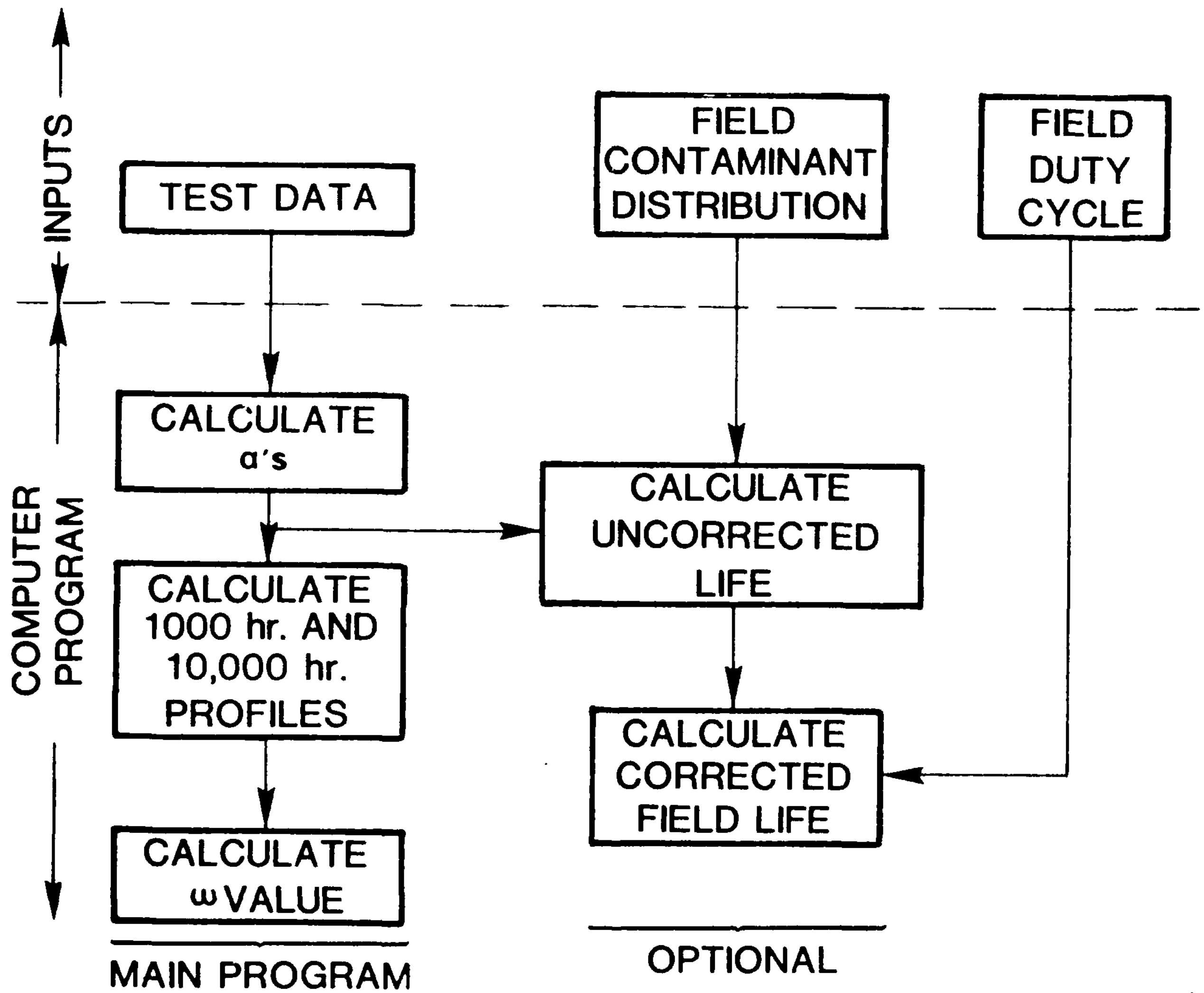

Fig. 10-1 Function of Relief Valve Contaminant Sensitivity Data Interpretation Computer Program

alternative constitutes the main body of the program, it will be discussed first.

Given the alpha values for the valve, the service life of a component can be determined by those methods presented earlier. This process can also be reversed, or, by inputting a desired service life, the contaminant distribution which will afford that requirement can be computed. This particular program determines the tolerable contaminant profiles, which will allow for 1000 and 10,000 hours of usable service life in the field. This branch of the program is further implemented by the omega rating program. Given the contaminant tolerance profile for a valve, the beta ten filter model which will condition the fluid to the level prescribed by the 1000 hour profile is calculated. Simply stated, the omega program determines the beta ten filter down stream contaminant distribution which is tangent to the extreme left point on the 1000 hour contaminant profile. In this way, the quality of filtration necessary to satisfactorily protect the valve can be determined. The omega value also provides a very discriminating rating system for all valves. As stated earlier, the profile and omega branch of the program are considered to be the main computational effort to be used in conjunction with the relief valve test.

The field distribution life branch of the program is a viable option for those users who know the contaminant distribution which a valve can be expected to meet in the field. For this instance, the field contaminant distribution life program is a worthwhile effort. Therefore, the calculation requires the values of the contaminant wear coefficients

as mentioned earlier along with the field contaminant distribution. Because the former quantities are internally generated, the latter is the only extraneous information required. This aspect has been simplified for the user by requiring only the number of particles of size greater than 5μm and 15μm which are expected in the field. In this way, the field distribution is modeled into a straight line distribution on the particulate contamination chart. Inputting this information along with the test data, the expected service life of the valve can be predicted.

A further expansion of this segment allows for those users who do not know the fluid contamination distribution but still desire an approximation of the expected field life of a valve given particular contamination levels. This is accomplished by substituting the AC Fine Test Dust distribution for the required particle numbers as listed above. This again will predict the service life of the component in question.

Still another option available along this branch is that of actual field duty cycle compensation on predicted service life. As should be remembered, all of the previously mentioned elements of the program assume the same operating conditions as those presented in the laboratory or continuous flow through the valve. Because this rarely is the case, the effect of duty cycle was desired. As described in Chapter IX, by knowing the pressure levels which will be used in the field, along with the pulsation characteristics of the system, the duty cycle can be accounted for. The actual input consists of the two correction

values which were described in Chapter IX, the flow correction factor and the exposure time correction factors. In this way, the actual operating conditions and contaminant distribution which the valve will encounter in the field are accounted for. Again, this option predicts the service life of a valve under the prescribed field conditions.

The program is presented in its entirity below.

APPENDIX [illegible] PROGRAM [illegible]

```
C          [illegible] (TIDN)

      DIMENSION [illegible] PE(9), [illegible]
     1[illegible] (6), NAME(40), [illegible] (2,13), [illegible] BLIF(6)
     2, [illegible] (7), WFACT( ), TX (9), IATA(2 ), RAT  ( ), SIZEX( ), DUMY(18)
      [illegible] /BLK1/ ALPHA(21), [illegible] (21), PO(22), P(9,9), [illegible] SIZE, [illegible]
     1 [illegible] (22)
      COMMON /BLK2/ ALIF [illegible]
      DATA [illegible]
     1[illegible] 1.0/
      DATA TX /0.,0.,48.,47.,36.,29.,22.,14.,9./
      SIZE=[illegible]
      PE0=2 .
      [illegible]=100.
      IMAX=[illegible]
      CALL FAKT
      CALL READM(WFACT,P  , T MP,V L,ANJ,AX L ,IATA,T)
      CALL C RR(WFACT,PO,IMAX,PE)
      CALL ALPH(ALPHA,PO,PF, ,F,T,TA ,IMAX)
      CALL PR FIL(ANDSAV, STD )
      DO 10 I=1,18
        SIZEX(I)=(AL [illegible] (18-I+1))**2
        IF (ANDSAV(1,18-I+1).GT. [illegible]) DUMY(I)=ALOG10(ANDSAV(1,18-I+1))
        IF (ANDSAV(1,18-I+1).LE. [illegible]) DUMY(I)=0.
10    CONTINUE
      CALL [illegible]ACA(SIZEX,DUMY, [illegible])
      DO 20 I=1,9
        STDP(I)=PE(I)/P [illegible]
20    CONTINUE
      CALL OUT(IATA,TEMP,V L,ANJ,AXLO, [illegible]),PF,STDP)
      CALL OUT2(IATA,ANDSAV,DST , [illegible])
      WRITE(6,30)
30    FORMAT(' DO YOU WISH TO [illegible] THE LIFE CALCULATION (1=YES, 0=NO)')
35    CONTINUE
      READ (1,*)ITEMP
      IF (ITEMP.NE.1)GOTO [illegible]
         AND05=X   - =5.9.
         AN 15=66 .1E2
         DO 37 KK=1,3
            CALL LIF(AND05,AND15, )
            IZAPU=10**KK
            WRITE(9,36)IZAPU,TLIFE
36          FORMAT(' FOR AD TO ',I ,' 45/L  LIFE=',1P,E13.2)
             IF (KK.EQ.2)TLIFE2=TLIFE
            AND05=AND05*10.
            AND15=AND15*10.
37       CONTINUE
         TLIFE=TLIFE2
         WRITE(6,46)TLIF
46       FORMAT(' TLIFE IS ',F10.4,' DO YOU WISH TO DO A DUTY CYCLE',/
     +    ' CALAULATION (1 FOR YES, 0 FOR NO)?')
         READ(1,*)IDUM
         IF (IDUM.NE.1) GOTO 55
            WRITE (6,47)
47          FORMAT(' ENTER FLOCOR')
            READ(1,*)FLOCOR
            WRITE (6,48)
```

```
48        FORMAT(' ENTER TIMCOR')
          READ(1,*)TIMCOR
          DCCOR=1./(FLOCOR*TIMCOR)
          TCOR=DCCOR*TLIFE
          WRITE(6,49)DCCOR,TCOR
          WRITE(9,49)DCCOR,TCOR
49        FORMAT(' FOR A DUTY CYCLE CORRECTION FACTOR OF ',1PE13.4,/
  +              ' THE EXPECTED FIELD SERVICE LIFE IS',E13.4)
      WRITE(9,51)FLOCOR,TIMCOR
51    FORMAT(' FLOCOR IS ',1PE13.4,' TIMCOR IS ',E13.4)
55 STOP
   END



      SUBROUTINE PART
      DIMENSION WR(11)
      COMMON /BLK1/ ALPHA(21),DIA(21),DP(22),P(9,9),PFD,NSIZE,GNORM,DI
     1ST(6,22)
      COMMON /BLK2/ ALIFE,TLIFE,AND,B,ILIFE,J,PO
      DATA WR/.39,.57,.73,.85,.91,.944,.963,.974,.982,.987,.99/
C     **SET PARTICLE SIZES TO DESIRED VALUES
      DIA(1)=5
      DO 10 I=2,NSIZE
10    DIA(I)=10*(I-1)
C     **CALCULATE PARTICLES IN INTERVAL (1-J) IN RANGE (0-K)
      DO 20 J=1,9
      ACFTD=1751.5431*(1.-EXP(-.471392*ALOG(DIA(J))**2))
      DO 20 K=J,9
      P(K,J)=0.
20    P(J,K)=ACFTD/WR(K)
C     **CALCULATE PARTICLES**2 FOR ALL INTERVALS FOR GNORM MG/L
      DO 30 JM=1,8
      J=10-JM
      DO 30 K=J,9
30    P(J,K)=((P(J,K)-P(J-1,K))*GNORM)**2
      DO 40 I=1,9
40    P(1,I)=(P(1,I)*GNORM)**2
      RETURN
      END
```

```
      SUBROUTINE READM(PF,REF,Q,TEMP,VOL,ANJ,AXFLO,IATA,T)
C     * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C     *                                                                   *
C     *                       READING SUBROUTINE                          *
C     *                                                                   *
C     * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
      DIMENSION PF(9),IATA(200)
      WRITE (6,50)
   50 FORMAT(' ENTER THE RELIEF VALVE THAT WAS TESTED')
      READ(1,40)(IATA(I),I=11,50)
      WRITE (6,60)
   60 FORMAT(' ENTER THE VALVE TYPE ')
      READ(1,40)(IATA(I),I=51,70)
      WRITE (6,70)
   70 FORMAT(' ENTER THE OSU-VALVE NUMBER')
      READ(1,40)(IATA(I),I=71,75)
      WRITE (6,30)
   30 FORMAT(' ENTER THE DATE ')
      READ(1,40)(IATA(I),I=1,10)
   40 FORMAT(100A1)
      WRITE(6,80)
   80 FORMAT(' ENTER THE TEMPERATURE ')
      READ(1,*)TEMP
      WRITE(6,90)
   90 FORMAT(' ENTER THE SYSTEM VOLUME ')
      READ(1,*)VOL
      WRITE (6,100)
  100 FORMAT(' ENTER THE GRAMS/INJECTION')
      READ(1,*)ANJ
      WRITE (6,110)
  110 FORMAT(' ENTER THE MAX RATED FLOW ')
      READ(1,*)AXFLO
      WRITE (6,20)
   20 FORMAT(' ENTER REF FLOW RATE')
      READ (1,*)Q
      WRITE (6,120)
  120 FORMAT(' ENTER THE INITIAL REF PRESSURE')
      READ (1,*) REF
      DO 10 NUM=1,9
      WRITE (6,5)NUM
      READ (1,*) PF(NUM)
    5 FORMAT(' ENTER PF ',I2)
   10 CONTINUE
      WRITE(6,130)
  130 FORMAT(' ENTER THE TIME(IN MIN.)')
      READ(1,*)T
      RETURN
      END
```

```
      SUBROUTINE CORR(UNCORR,FSTCOR,ISIZE,CORREC)
C     * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C     *                                                               *
C     *                  DATA CORRECTION SUBPROGRAM                   *
C     *                  FLUID POWER REASEARCH CENTER                 *
C     *                            O.S.U                              *
C     *                      LAST UPDATE 800814                       *
C     *                                                               *
C     * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C     THIS SUBROUTINE IS A DATA CORRECTION SUBROUTINE. IT FINDS DATA
C     POINTS THAT ARE ABOVE PREVIOUS DATA POINTS AND MOIVES THEM DOWN TO
C     A POINT EQUAL TO THE PRIVIOUS DATA POINT, IT THEN MOVES DOWN ALL
C     FOLLOWING DATA POINTS BY AN EQUAL PERCENTAGE AMOUNT. AFTER EACH
C     PASS THROUGH THE DATA POINTS IT CHECKS TO SEE IF THERE HAVE BEEN
C     ANY CORRECTIONS MADE ON THIS PASS, IF THERE HAVE BEEN IT MAKES AN
C     ANOTHER PASS CHECKING FOR DATA POINTS OUT OF LINE.  THIS PROCESS IS
C     CONTINUED UNTILL NO CORRECTIONS ARE MADE.
C
C
C        INPUTS :
C                 UNCORR - UNCORRECTED DATA ARRAY
C                 FSTCOR - THE NUMBER THAT THE FIRST DATA POINT IS
C                          COMPARED TO.
C                 ISIZE  - THE ARRAY SIZE OF UNCORR AND CORREC
C
C       OUTPUTS : CORREC - THE CORRECTED DATA ARRAY
C
C         LOCAL : FACTOR - THE CORRECTION FACTOR
C
      DIMENSION UNCORR(ISIZE),CORREC(ISIZE)
C     SET CORREC EQUAL TO UNCORR
      DO 5 I=1,ISIZE
          CORREC(I) = UNCORR(I)
    5 CONTINUE
C     SET THE CORRECTION FACTOR EQUAL TO 100 PERCENT
      FACTOR = 1
      IF (CORREC(1).GT.FSTCOR) FACTOR = FSTCOR/CORREC(1)
      CORREC(1) = CORREC(1)*FACTOR
   10 CONTINUE
C     START DO-LOOP TO CHECK AND CORRECT DATA POINTS FROM 2 TO ISIZE
      DO 15 I=2,ISIZE
          IF (CORREC(I).GT.CORREC(I-1).AND.FACTOR.EQ.1.0)
     +         FACTOR = CORREC(I-1)/CORREC(I)
          CORREC(I) = CORREC(I)*FACTOR
   15 CONTINUE
C     RETURN IF NO CORRECTIONS HAVE BEEN MADE
      IF (FACTOR.EQ.1.0) RETURN
C     SET CORRECTION FACTOR EQAL TO 100 PERCENT AND MAKE ANOTHER PASS
      FACTOR = 1.0
      GO TO 10
      END
```

```
      SUBROUTINE ALPH(ALPHA,PO,PF,Q,P,T,TAU,IMAX)
C     ******************************************************************
C     *                                                                *
C     *                  ALPHA CALCULATION SUBPROGRAM                  *
C     *                  FLUID POWER RESEACH CENTER                    *
C     *                           O.S.U.                               *
C     *                     LAST UPDATE 800814                         *
C     *                                                                *
C     ******************************************************************
C
C     THIS SUBROUTINE CALCULATES THE WEAR COEFFICIENTS FOR A RELIEF VALVE
C     . THE EQ. WERE DERVIED AT THE FLUID POWER RESEARCH CENTER IF YOU
C     HAVE ANY QUESTIONS ABOUT THEM PLEASE CALL US AT 405-624-7375.
C
C          INPUTS :
C                      PO     - RATED PRESSURE OF THE VALVE
C                      PF     - ARRAY OF FINAL PRESSURES
C                      Q      - FLOW
C                      P      - ARRAY CONTAINING PARTICLE COUNTS SQUARED
C                      T      - TIME IN MINUTES
C                      TAU    - CONTAMINANT DESTRUCTION RATE TIME CONSTANT
C                      IMAX   - NUMBER OF INJECTIONS
C
C        OUTPUTS :
C                      ALPHA  - ARRAY OF CONTAMINANT WEAR COEFFICIENTS
C
C          LOCAL :
C                      ITEMP  - TEMPORARY VAR. FOR DO-LOOP COUNTER
C                      TEMP   - TEMPORARY VAR. FOR SUMATION OF ALPHA
C
      DIMENSION ALPHA(21),PF(IMAX),P(IMAX,IMAX),TAU(IMAX)
C
      ALPHA(1) = (PO-PF(1))/(P(1,1)*Q*T)
      ALPHA(2) = (1/P(2,2))*(((PO-PF(2))/(Q*T))-ALPHA(1)*P(1,2))
      ALPHA(3) = 2*(PF(3)-PO+Q*T*(ALPHA(1)*P(1,3)+ALPHA(2)*P(2,3)))/(Q*
     +           P(3,3)*TAU(3)*(EXP(-2*T/TAU(3))-1))
      DO 10 I=4,IMAX
          ITEMP = I-1
          TEMP = 0.
          DO 5 J=3,ITEMP
              TEMP = ALPHA(J)*P(J,I)*TAU(J)*(EXP(-2*T/TAU(J))-1)+TEMP
 5        CONTINUE
          ALPHA(I) = 2*(PF(I)-PO+Q*T*(ALPHA(1)*P(1,I)+ALPHA(2)*P(2,I))-
     +               .5*Q*(TEMP))/(Q*P(I,I)*TAU(I)*(EXP(-2*T/TAU(I))-1))
   10 CONTINUE
C     SET ALL REMAINING ALPHAS EQUAL TO ALPHA(IMAX)
      ITEMP = IMAX+1
      DO 15 I=ITEMP,21
          ALPHA(I) = ALPHA(IMAX)
   15 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE PROFIL(ANDSAV,DSTORE)
C     * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C     *                                                               *
C     *                 CONTAMINANT TOLERANCE PROFILE                 *
C     *                 FLUID POWER RESEARCH CENTER                   *
C     *                           O.S.U.                              *
C     *                    LAST UPDATE 800914                         *
C     *                                                               *
C     * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
      DIMENSION ANDSAV(2,18),DSTORE(18)
      COMMON /BLK1/ ALPHA(21),CIA(21),DP(22),P(9,9),PFD,NSIZE,GNORM,DI
     1ST(6,22)
      COMMON /BLK2/ ALIFE,TLIFE,AND,D,ILIFE,Q,PO
      ALIFE = 1000.0
      DO 260 K=1,2
         DO 215 I=1,18
           ANDSAV(K,I)=0
  215    CONTINUE
         LOCAL = 2
         AND = .01
         ILIFE = 1
         BL = .3
         DO 255 I=1,18
           BMIN = BL
           BMAX = BMIN+.5
           REDUC = .01/(BMAX-BMIN)
           D = DSTORE(I)
  230      CALL GCLD(BMIN,BMAX,REDUC,DIFF,BGOOD,BL,BR,NN,LOCAL)
           IF (ILIFE.EQ.2) GOTO 235
             ILOG = ALOG10(AND)
             IF (ILOG.LT.0) ILOG=ILOG-1
             ANI = 2.0*10.**ILOG
             AND = AND+ANI
             GOTO 230
  235      IF (AND.EQ.0.01) GOTO 255
             ANMIN = AND-ANI
             ANMAX = AND
             AND = AND-ANI/2.
             DO 245 J=1,25
               CALL GCLD(BMIN,BMAX,REDUC,DIFF,BGOOD,BL,BR,NN,LOCAL)
               IF (ILIFE.EQ.2) GOTO 240
                 BMIN = BL
                 REDUC = 1.0E-3/(BMAX-BMIN)
                 ANMIN = AND
                 GOTO 245
  240          IF (DIFF/ALIFE.GE.-0.01) GOTO 250
                 ANMAX = AND
  245            AND = (ANMAX+ANMIN)/2.
  250        IF (J.LT.25) ANDSAV(K,I) = AND
             IF (AND.GT.1.E+10) GOTO 260
             AND = AND + ANI
  255    CONTINUE
         ALIFE = 10000.0
  260 CONTINUE
      RETURN
      END
```

```
      FUNCTION FX (X)
      IF (X.GT.5.) GO TO 10
      C=X*SQRT(2./(4.*ATAN(1.)))
      FX=C
      N=2
      I=-1
      F=1
    5 SUM=C*(I*X**N)/(2.**(N/2)*F*(N+1))
      FX=FX+SUM
      IF (ABS(SUM/FX).LE.1.E-8) GO TO 15
      N=N+2
      I=-I
      F=F*(N/2)
      GO TO 5
   10 FX=1
      RETURN
   15 FX=0.5+FX/2.
      RETURN
      END
```

```
      SUBROUTINE LIFE (DI,B,IP)
      COMMON /BLK1/ ALPHA(21),DIA(21),DP(22),P(9,9),PFD,NSIZE,GNORM,DI
     1ST(6,22)
      COMMON /BLK2/ ALIFE,TLIFE,AND,D,ILIFE,Q,PO
      DIMENSION FN(10)
      IF (IP.EQ.2) GO TO 10
      PD1=DI
      DO 5 I=1,NSIZE
      PD2=ALOG(DI)+(-B*ALOG(DIA(I))**2)
      PD2=EXP(PD2)
      FN(I)=PD1-PD2
    5 PD1=PD2
      GO TO 20
   10 DO 15 I=1,NSIZE
   15 FN(I)=DP(I)-DP(I+1)
   20 SUM=0
      DO 25 J=1,NSIZE
      IF (FN(J).LT.1.E-30) FN(J)=0.
   25 SUM=SUM+ALPHA(J)*FN(J)*FN(J)
      TLIFE=((PFD*PO)/(100.*Q))/(60.*SUM)
      RETURN
      END
```

```
      SUBROUTINE GOLD (XL,XR,F,YBIG,XBIG,XL1,XR1,N,LOCAL)
      COMMON /BLK1/ ALPHA(21),DIA(21),DP(22),P(9,9),PFD,NSIZE,GNORM,DI
     1ST(6,22)
      COMMON /BLK2/ TLIFE,ALIFF,AND,D,ILIFE,Q,PO
5     N=0
      XLEFT=XL
      XRIGHT=XR
      SPAN=XR-XL
      DELTA=ABS(SPAN)
10    X1=XL+0.381966*DELTA
      X2=XL+0.618034*DELTA
      CALL MERIT1 (X1,Y1)
      IF (ILIFE.EQ.1.AND.LOCAL.EQ.2) GO TO 60
      CALL MERIT1 (X2,Y2)
      IF (ILIFE.EQ.1.AND.LOCAL.EQ.2) GO TO 60
      N=N+2
15    IF (ABS(XL-XR)-ABS(F*SPAN)) 35,35,20
20    DELTA=0.618034*DELTA
      IF (Y1-Y2) 25,55,30
25    XL=X1
      X1=X2
      Y1=Y2
      X2=XL+0.618034*DELTA
      CALL MERIT1 (X2,Y2)
      IF (ILIFE.EQ.1.AND.LOCAL.EQ.2) GO TO 60
      N=N+1
      GO TO 15
30    XR=X2
      Y2=Y1
      X2=X1
      X1=XL+0.381966*DELTA
      CALL MERIT1 (X1,Y1)
      IF (ILIFE.EQ.1.AND.LOCAL.EQ.2) GO TO 60
      N=N+1
      GO TO 15
35    IF (Y2-Y1) 40,40,45
40    YBIG=Y1
      XBIG=X1
      GO TO 50
45    YBIG=Y2
      XBIG=X2
50    XL1=XL
      XR1=XR
      GO TO 60
55    XL=X1
      XR=X2
      DELTA=XR-XL
      GO TO 10
60    XL=XLEFT
      XR=XRIGHT
      RETURN
      END
```

```
      SUBROUTINE MERIT1 (B,DIFF)
      COMMON /BLK1/ ALPHA(21),CIA(21),DP(22),P(9,9),PFD,NSIZE,GNORM,DI
     1ST(6,22)
      COMMON /BLK2/ ALIFE,TLIFE,AND,D,ILIFE,Q,PO
      DI=AND*EXP(B*ALOG(D)**2)
      ILIFE=2
      CALL LIFE (CI,B,1)
      IF (TLIFE.GT.1.C1*ALIFE) ILIFE=1
      DIFF=-ABS(TLIFE-ALIFE)
      RETURN
      END



      SUBROUTINE OUT(IATA,TEMP,VOL,ANJ,AXFLD,QZERO,ANITAL,PRESSU,RATIO)
      DIMENSION IATA(200),PRESSU(9),RATIO(9)
      WRITE (9,10)(IATA(I),I=1,75)
   10 FORMAT('1RELIEF VALVE CONTAMINANT SENSITIVITY TEST RESULTS '///,
     +       'ODATE TESTED:',10A1,' TEST LOCATION: FPRC-OSU '/,
     +       ' RELIEF VALVE TESTED:',40A1,/
     +       ' VALVE TYPE:',20A1,' CSU-VALVE NO.:',5A1)
      WRITE (9,20)TEMP,VOL,ANJ,AXFLO,QZERO,ANITAL
   20 FORMAT(' FLUID TEMPERATURE:',F5.1,'F    SYSTEM VOLUME:',F4.1,'LITTE
     +RS',/  ' TEST FLUID: MIL-L-2104 CLASS 10  GRAMS/INJECTED :',F4.1,/
     +       ' FLUID VISCOSIY: 15.2 CST  GRAV.LEVEL: 100 MG/L '/,
     +       ' MAX RATED FLOW:',F5.1,'GPM',/
     +       ' REF FLOW RATE:  ',F5.1,'GPM',/
     +       ' INITIAL REF PRESSURE:',F8.1,'PSI',/
     + ///   'OSIZE INJECTED',T20,' REF PRESSURE',T35,' PRESSURE DEGRADA
     +TION',/' (MICROMETERS)',T20,'      (PSI)    ',T35,'        RATIO')
      KOUNT=5
      DO 30 I=1,9
         WRITE (9,25)KOUNT,PRESSU(I),RATIO(I)
   25    FORMAT('        0-',I2,T22,F8.1,T41,F8.3)
         IF (KOUNT.EQ.5) KOUNT=0
         KOUNT=KOUNT+10
   30 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE OUT2(IATA,ANDSAV,DSTORE,OMAG)
      DIMENSION IATA(200),ANDSAV(2,18),DSTORE(18)
      WRITE (9,10)(IATA(I),I=1,75)
   10 FORMAT('1RELIEF VALVE CONTANINANT SENSITIVITY DATA INTERPRETATION'
     + ,///  ' DATE TESTED:',10A1,' TEST LOCATION: FPRC-OSU '
     + ,/     ' RELIEF VALVE TESTED: ',40A1
     + ,/     ' VALVE TYPE :',20A1,'OSU-VALVE NO.:',5A1
     + ,///  ' RELIEF VALVE CONTAMINANT TOLERANCE PROFILE ',
     + //    T20,' 1000 HOUR',T35,'10,000 HOUR',
     + / ' PARTICLE',T20,'NO.PARTICLES',T35,'NO.PARTICLES',/
     +    ' SIZE. MIC.',T20,'>SIZE/ML.',T35,'>SIZE/ML.')
      WRITE (9,20)(DSTORE(I),ANDSAV(1,I),ANDSAV(2,I),I=1,18)
   20 FORMAT(1H ,0PF5.1    ,T18,1PE13.4,T33,1PE13.4)
      IF (OMAG.LT.1.5) WRITE (9,30) OMAG
      IF (OMAG.GE.1.5) WRITE(9,40) OMAG
   30 FORMAT(///T20,' TEST OMEGA = ',F6.4//////)
   40 FORMAT(///T20,' TEST OMEGA = ',F6.1//////)
      RETURN
      END



      SUBROUTINE CMAGA(SIZEX,NUMY,BETA)
      DIMENSION SIZEX(18),NUMY(18)
      IF (NUMY(1).LT.3.0) GOTO 1010
      SLOPE=-2.64
      YSEC=7.81
      J=1
      I=0
  950 I=I+1
      SLOPEX=(NUMY(I+1)-NUMY(I))/(SIZEX(I+1)-SIZEX(I))
      IF (SLOPEX.LT.-3.82) GOTO 950
      I=I-1
  960 I=I+1
  970 YFLT=SLOPE*(SIZEX(I))+YSEC
      DD=YFLT-NUMY(I)
      IF (DD.LE.0.0) GOTO 980
      J=J+1
      IF(J.LE.10) GOTO 971
      IF (J.GT.10.AND.J.LE.19) GOTO 972
      IF (J.GT.19.AND.J.LE.27) GOTO 973
      IF (J.GT.27.AND.J.LE.36) GOTO 974
      IF (J.GT.36.AND.J.LE.45) GOTO 975
      SLOPE=-3.43-(0.32/9.0)*(J-45)
      YSEC=3.60-(0.68/9.0)*(J-45)
      GOTO 970
  971 SLOPE=-2.64-(0.06/9.0)*(J-1)
      YSEC=7.81-(0.93/9.0)*(J-1)
      GOTO 970
  972 SLOPE=-2.70-(0.29/9.0)*(J-10)
      YSEC=6.88-(0.72/9.0)*(J-10)
      GOTO 970
  973 SLOPE=-2.99-(0.03/8.0)*(J-19)
      YSEC=6.16-(0.97/8.0)*(J-19)
      GOTO 970
  974 SLOPE=-3.02-(0.31/9.0)*(J-27)
      YSEC=5.19-(0.68/9.0)*(J-27)
      GOTO 970
  975 SLOPE=-3.33-(0.10/9.0)*(J-36)
```

```
      YSEC=4.51-(C.91/9.0)*(J-36)
      GOTO 970
  980 YNEXT=SLOPE*(SIZEX(I+1))+YSEC
      DNEXT=YNEXT-NUMY(I+1)
      IF (DD.LT.DNEXT) GOTO 960
      IF (DD.LT.-C.2) GOTO 990
      IF (J.LE.10) BETA=1.01+0.01*(J-1)
      IF (J.GT.1C.AND.J.LE.19) BETA=1.10+0.1*(J-10)
      IF (J.GT.19.AND.J.LE.27) BETA=2.0+1.0*(J-19)
      IF (J.GT.27.AND.J.LE.35) BETA=10.*(J-26)
      IF (J.GT.36.AND.J.LE.45) BETA=100.*(J-35)
      IF (J.GT.45) BETA=10CC.*(J-44)
      X94=AMEAN-SC
      GOTO 1030
  990 WRITE(9,995)
  995 FORMAT(' DISTRIBUTION IS OUT OF RANGE')
      GOTO 1030
 1010 WRITE (9,995)
 1C30 CONTINUE
      RETURN
      END


      SUBROUTINE LIF(AND05,AND15)
      COMMON/BLK1/ALPHA(21),DIA(21),DP(22),P(9,9),PFD,NSIZE,GNORM,DIST(6
     +,22)
      COMMON/BLK2/ ALIFE,TLIFE,AND,D,ILIFE,Q,PO
      DIMENSION FN(21)
      B=ALOG(AND05/AND15)/4.7+32
      DI=AND05/EXP(-B*2.5903)
      PD1=DI
      DO 5 I=1,NSIZE
        PD2=DI*EXP(-B*ALOG(DIA(I))**2)
        FN(I)=PD1-PD2
        PD1=PD2
    5 CONTINUE
      SUM=0.
      DO 25 J=1,NSIZE
        IF(FN(J).LT.1.E-30) FN(J)=0.
        SUM=SUM+ALPHA(J)*FN(J)*FN(J)
   25 CONTINUE
      TLIFE=((PFD*PO)/(100.*Q))/(60.*SUM)
      RETURN
      END
```

CHAPTER XI

A GENERAL COMPARISON OF THE CONTAMINANT SENSITIVITY OF DIRECT-ACTING AND PILOT-OPERATED RELIEF VALVES

This chapter presents a general discussion of the effects of contaminant on the performance of the relief valves which have been tested during this project. The format will be to discuss the contaminant sensitivity of direct acting relief valves, the contaminant sensitivity of pilot-operated relief valves, and finally a direct comparison of both. The latter segment will consist of the test results which have been generated during the testing period along with the data interpretation results by the methods described in Chapter VI-X.

The relief valves which have been evaluated using the new test method (Chapter V) were donated by nine separate manufacturers. Of the eleven valves evaluated, four were direct acting valves, and the remaining seven were pilot operated valves.

The degradation characteristics which the direct-acting relief valves exhibited were relatively consistent for all four valves. For each, contaminant wear resulted in the gradual reduction of the entire pressure/flow characteristics of the valve from the original values. In other words, the pressure/flow profiles following injections of contaminant were similar in shape to the original profile, except for the magnitude of the pressure at the same relief flow.

An example of the pressure/flow degradation for a direct-acting

relief valve is shown in Fig. 11-1. Degradation of this type does not pose an immediate threat to the proper operation of a system. The major problem is the increase in leakage flow which results from contaminant wear.

Because fluid power users are working to increase the energy efficiency of systems, this type degradation cannot be tolerated due to the resulting increase in power loss which this degradation causes. A final comment on the contaminant sensitivity of direct-acting relief valves deals with phenomenon of contaminant lock. This was explained in earlier sections to be practically non-existent for direct-acting valves. This proposition was verified by the direct-acting valves which were tested. Therefore, of the two modes of contaminant sensitivity, contaminant wear effects are the most detrimental to the proper operatior of direct-acting relief valves.

Considering the contaminant sensitivity of pilot-operated relief valves, due to their self-regulating properties, these valves were observed to have more problems than direct-acting valves. Contaminant wear was seen to have marked effects on the performance of pilot-operated valves. Fig. 11-2 and 11-3 illustrate the degradation of the pressure/flow profiles for two different kinds of pilot-operated valves. For those valves which exhibited the pressure/flow characteristics similar to Fig. 11-2, the initial portion of the pressure/flow profile was observed to degrade more severely than the flat, level portion of the curve. For these valves, obviously, the pilot stage of the valve

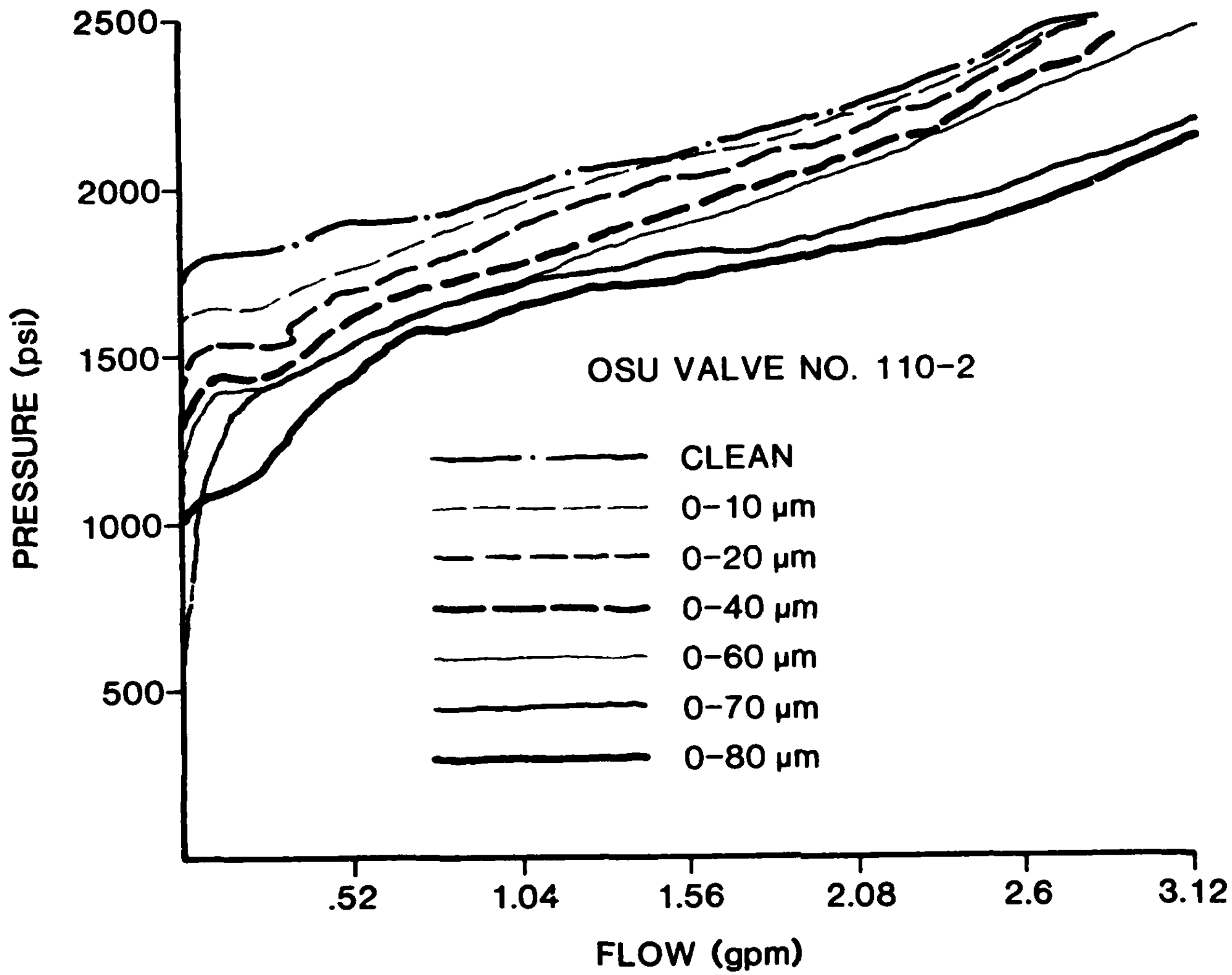

Fig. 11-1 Typical Performance Degradation of a Direct-Acting Relief Valve Due to Contaminant

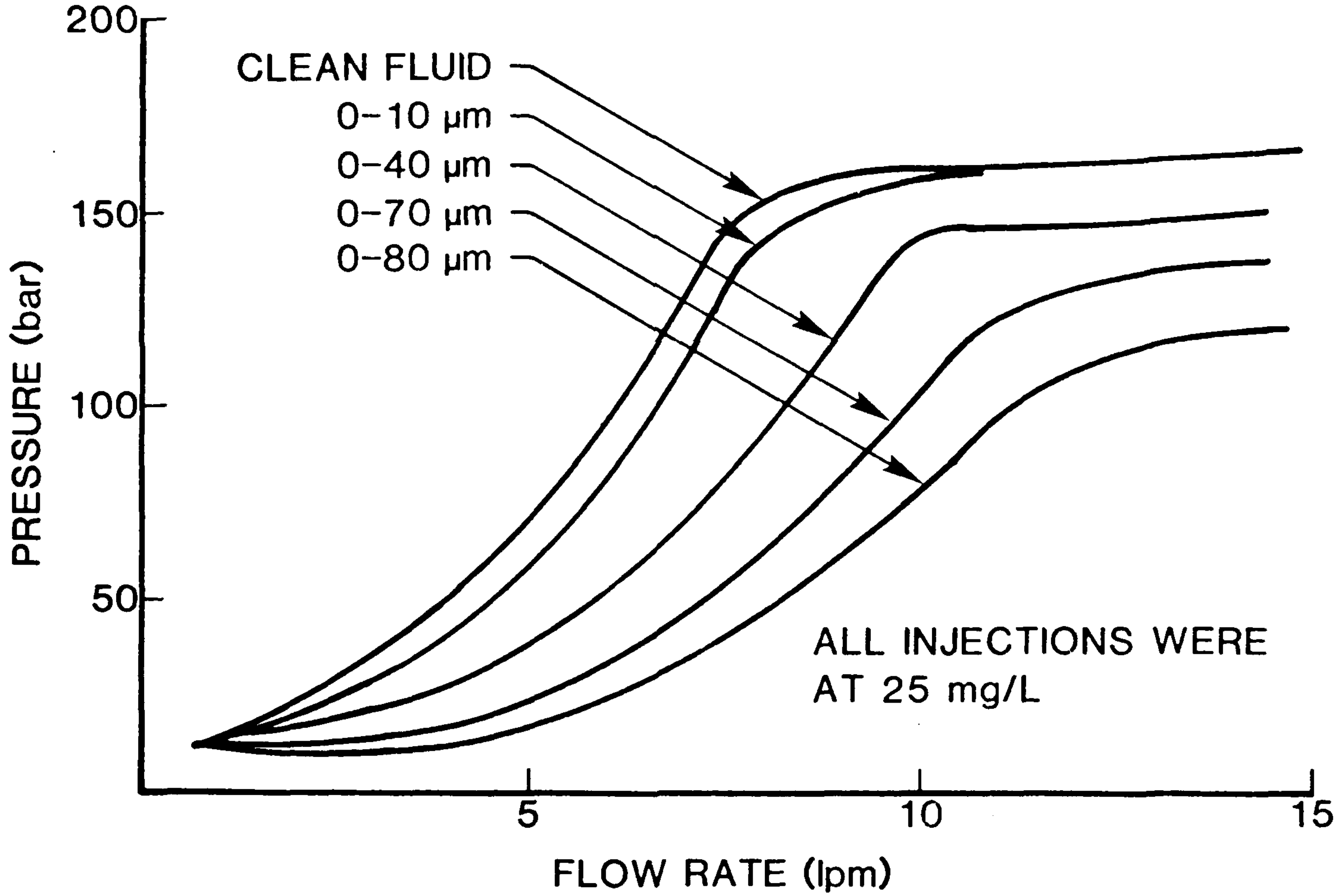

Fig. 11-2 Typical Performance Degradation of a Pilot-Operated Relief Valve
Due to Contaminant Wear

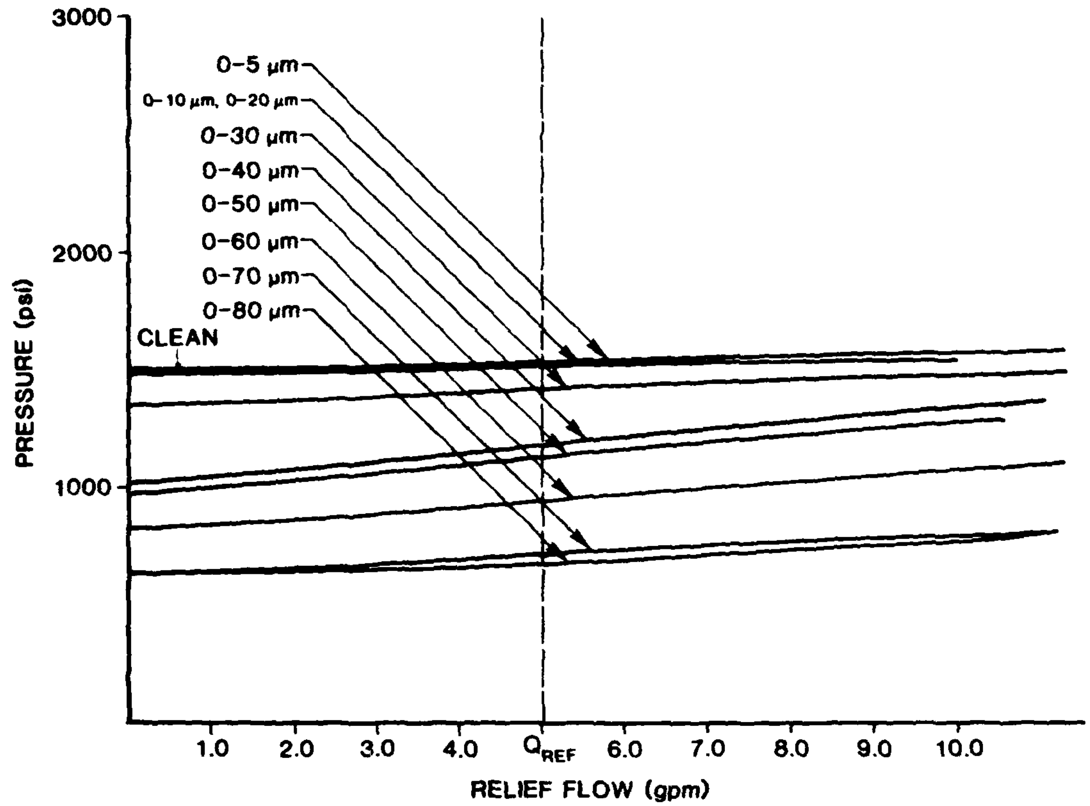

Fig 11-3 Typical Performance Degradation of a Pilot-Operated Relief Valve Due to Contaminant Wear

is the first to be effected by contaminant wear. Because this stage of the valve is essentially a direct-acting relief valve, its wear tendencies are similar to those of separate direct-acting valves.

Pilot operated relief valves are generally selected for use in systems requiring a constant level of system pressure. Because of the alteration of the pilot-controlled segment of the pressure/flow profile, the consistent pressure characteristics of these valves are destroyed.

For those valves exhibiting the pressure/flow characteristics similar to Fig. 11-3, performance degradation due to contaminant wear was also observed to occur in a consistent manner. With these, as with direct-acting valves, the degraded pressure/flow profiles are very similar to the original profile before wear, the major difference being the degraded pressure levels for the same relief flow. The increased power losses are subsequently the major concern due to this type performance degradation.

One point concerning the contaminant sensitivity of pilot-operated valves which is drastically different than direct-acting valves is the contaminant lock sensitivity. In several valves which were tested after the pressure was reduced following a period of high pressure at which the relief valve was completely open, the control elements inside the valve would not return to their normal positions. This resulted in two effects; 1) pressure could not be built in the system, and 2) even for extremely low pressures, sizable quantities of fluid would pass through

the valve. This condition probably was the result of the main control piston of the valve silting in its extreme open position. This can explain both characteristics above. The silt can, however, be eliminated by agitating the valve body in such a way that lateral vibration is applied to the main control spool or piston. Although the occurrence of a silt in moderately clean fluid is almost negligible, this susceptibility should not be overlooked.

Thus, for pilot-operated relief valves, although contaminant lock is a real possibility, contaminant wear is an inevitable occurrence and thus demands the more serious consideration.

As an initial statement concerning the relative sensitivity of pilot-operated and direct-acting relief valves, in general, pilot-operated valves are more seriously damaged due to fluid contaminants. To illustrate this point, Fig. 11-4 shows the pressure degradation ratios versus contaminant size per injection for the 11 relief valves tested. Close examination of this plot reveals some interesting statistics. For those valves tested, the only ones which degraded more than 20% over the entire course of the test were pilot-operated valves. This provides for the reasonable conclusion that pilot-operated valves, in general, are more sensitive to contaminant than direct-acting valves.

To determine particle size sensitivity, the order in which the test valves degraded more than 10% was considered. Fig. XI-5 illus-

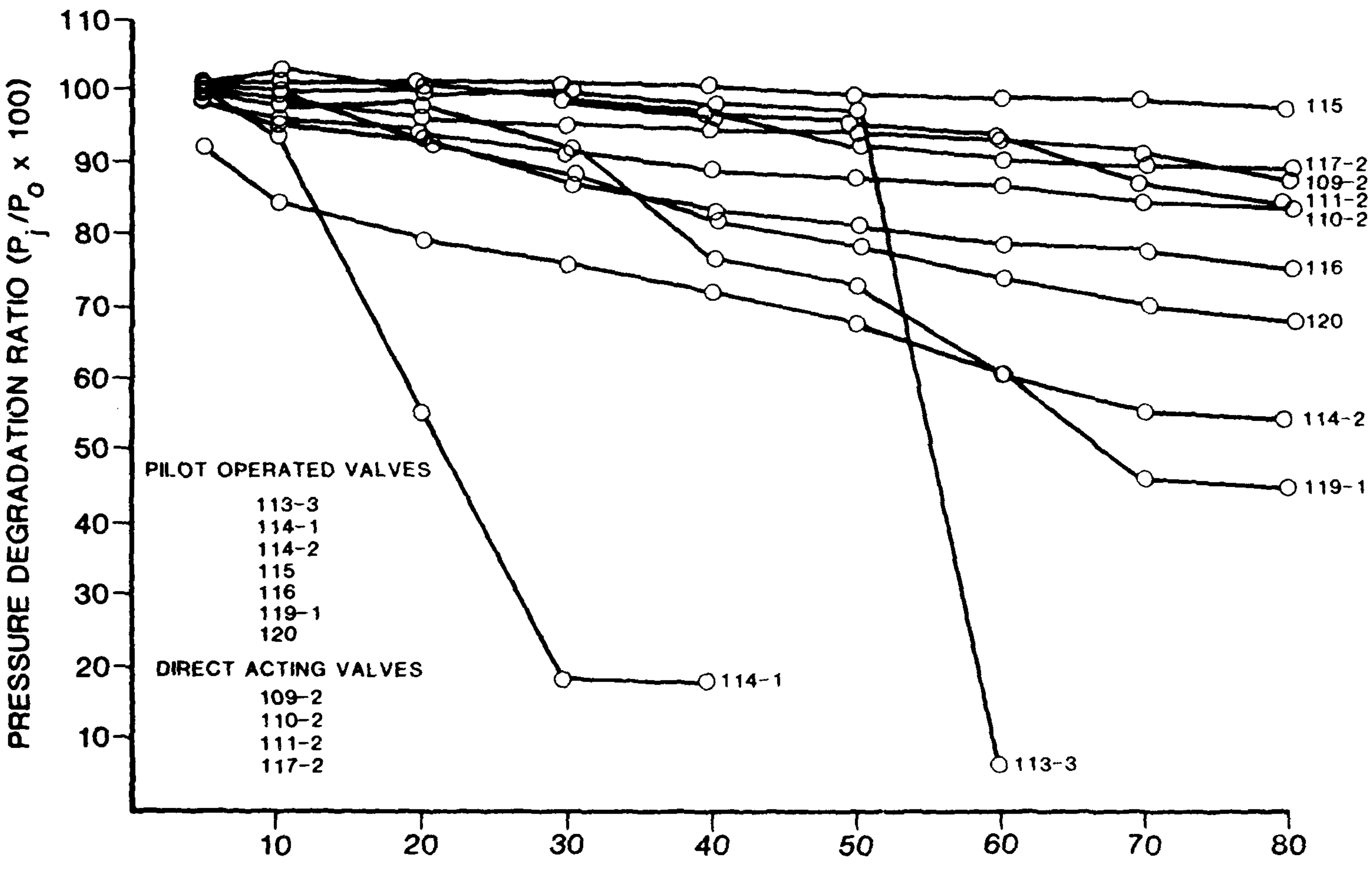

Fig. 11-4 Relief Valve Contamirant Sensitivity Test Results

PERFORMANCE DROPPED BELOW 90% FOLLOWING THE INJECTION SIZE BELOW	OSU VALVE NO.
0–5 μm	—
0–10 μm	114–2
0–20 μm	114–1,
0–30 μm	116, 120
0–40 μm	119–1, 110–2
0–50 μm	—
0–60 μm	113–3
0–70 μm	111–2
0–80 μm	109–2

Fig. 11-5 Contaminant Size Effects Analysis

trates this analysis. Those valves which are direct-acting have been circled to distinguish them from the pilot-operated valves. As can be seen, the first relief valve to degrade 10% was a pilot-operated design. This occurred after an injection of 0-10μm contaminant. Only after an injection of 0-40μm contaminant did a direct-acting valve degrade to this extent. The majority of the direct-acting valves which degraded more than 10% did so only after the contaminant injection of 0-70μm. In comparison, by this size injection, all of the pilot-operated valves which degraded 10% had already done so. This occurrence points to the conclusion that the pilot-operated valves which were tested were more sensitive to small size contaminant particles than the direct-acting valves which were tested.

Proceeding to the illustration of the computer aided evaluation of the test results, Fig. 11-6 presents the computer generated 1000 hour contaminant tolerance profiles for all of the valves which were tested. The most important point which should be drawn from the observation of this graph is the variations in the tolerance profiles for each valve. In no instance to two valves display the same contaminant tolerance profiles. This is consistent with the results of the actual degradation data illustrated in Fig. 11-4. As discussed in Chapter VIII, these profiles can be used to select the beta ten filters which can adequately protect the valve in question. These filter values are referred to as the omega values. The omega values for all the valves which were tested are presented in Table 11-7. Also

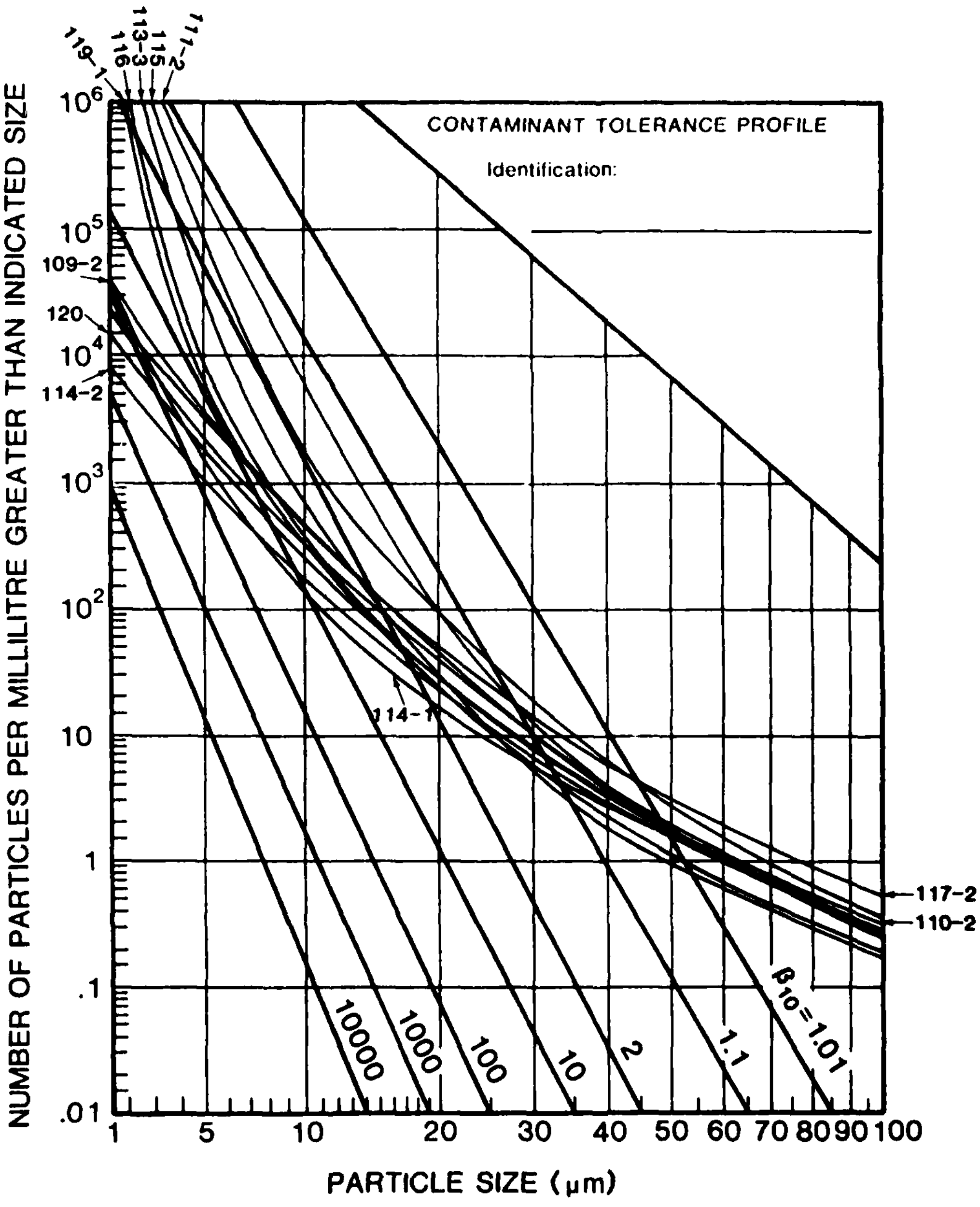

Fig. 11-6 Contaminant Tolerance Profiles for 1000 Hour Service Life

Table 11-7 OSU Relief Valve Contaminant Sensitivity Test Log

OSU VALVE NO.	OMEGA RATING	RANK
★ 109-2	65	6
★ 110-2	178	9
★ 111-2	1.2	1
★★ 113-3	4.0	3
★★ 114-1	86	8
★★ 114-2	422	11
★★ 115	3.0	2
★★ 116	6.0	4
★ 117-2	74	7
★★ 119-1	15	5
★★ 120	302	10

★ DIRECT ACTING RELIEF VALVE

★★ PILOT OPERATED RELIEF VALVE

listed in the table is the relative ranking of these valves in comparison to the others. Because the omega value represents the degree of sensitivity to small contaminant particles, those valves which displayed a low omega rating can therefore be considered to be relatively insensitive to small particles. At the other extreme, those valves with high omega ratings are extremely sensitive to small contaminants and thus are much harder to protect in the field.

Briefly summarizing, this chapter has presented the test results from 11 relief valve contaminant sensitivity tests conducted as described in Chapter V. This consisted of a direct degradation versus contaminant size analysis and a computer generated contaminant tolerance profile for each valve. This method provides a powerful new tool for hydraulic engineers and designers in the selection of quality components.

CHAPTER XII

RECOMMENDATION AND CONCLUSION

The conclusions which have been drawn as a result of this research effort can be summarized as below:

1. The previously used relief valve contaminant sensitivity test and assessment procedure are unfit for industry standardization and as such should no longer be considered viable alternatives for relief valve contaminant sensitivity studies.
2. Although pressure relief valves are susceptible to the occurence of contaminant lock, this form of contaminant sensitivity is much less harmful to the long-term operation of these valves than the ever-existant contaminant wear process.
3. Of the two modes of contaminant wear which occur in relief valves, erosive wear effects have been determined to be much more significant than the effects of three-body abrasive wear.
4. The Relief Valve Degradation Theory presented in Chapter VI accurately represents the performance degradation of relief valves due to contaminant wear effects. Therefore, this theory should be the basis for any subsequent assessment procedure for the contaminant sensitivity of relief valves.
5. Generally speaking, for those relief valves which were tested, pilot-operated designs were observed to be more sensitive to fluid contamination than direct-acting designs.

Because the Relief Valve Contaminant Sensitivity Assessment Procedure presented in this report adequately fulfills all of the objectives proposed for this contract, it is recommended that it be considered as a Military Specification test procedure. It is also highly recommended MERADCOM provide additional funding so that this technique can be promoted through SAE subcommittee by the FPRC for acceptance as an SAE recommended practice.

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